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MARINER R RELIABILITY MODEL FORMULATION AND QUALITATIVE ASSESSMENT

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PLANNING RESEARCH CORPORATION
LOS ANGELES, CALIFORNIA WASHINGTON, D. C.

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By

James D. Andrew,
Peter D. Hume and
Stanley H. Smith

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ABSTRACT

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The report covers an investigation of the Mariner R spacecraft as configured for a Venus-approach mission. A model of system reliability is developed in order to perform quantitative analyses of the performance expected in view of certain stated objectives for the complete mission. Exercising of the model, with numerical data, is not covered in this report: it is intended that this be carried out at a later date. A qualitative appraisal of the vehicle and its mission is included in the report; this is work which naturally parallels the development of the model and certain significant outcomes of the qualitative assessment lead to some recommendations for system modifications of a practicable nature. This study has been conducted by Planning Research Corporation as a subcontractor to the Jet Propulsion Laboratory, which is responsible for the Mariner programs.

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I. INTRODUCTION

A. Study Objectives

The Mariner R spacecraft is a project of Jet Propulsion Laboratory, intended to supply NASA with the capability of achieving planetary research by close approaches to Venus. Scientific data is to be collected during the approaches and, as a bonus, during the interplanetary stages of the flights. Extensive telemetry is incorporated, both for the scientific data and for monitoring the on-board systems and structures of the vehicle throughout the operation.

(For the convenience of readers who are not acquainted with the Mariner R system and the 1962 flight to Venus some brief descriptions are contained in Appendix A of this report.)

The material presented here is the outcome of a preliminary study concerning the reliability of the spacecraft and its mission. This study has as its prime purpose the formulation of a model of the Mariner R system and flight profile. Numerical application of this model is excluded; it is, however, used as a basis for a qualitative assessment of the probability that the mission will realize certain planned objectives. In addition, it is intended that any matters bearing on the chances of success be noted as recommendations so that future versions of the Mariner (or kindred systems) may incorporate the best design features that the inevitable constraints will permit.

B. Summary of Study Approach

The formulation of the reliability model is performed in a manner adapted to the special characteristics of the Mariner R mission. The approach taken allows probability values to be derived not only for the planned configuration of events and experiments, but also for the performance of a range of subnormal, or degraded missions, such as may well occur in view of the present state of the art. A classical, or mean-time-to-failure model involving a static configuration of all the necessary subsystems, is considered to be unsuitable for the assessment desired in this work. The adopted figure-of-merit[1] model is capable of manipulation in spite of the many variations in performance of essential functions which are considered to be pertinent to this context.

In the present approach, the complete mission is divided into four phases, which are serial in time. In each phase certain functions have to be accomplished, and systems as appropriate will thus be required to perform distinct processes. The reliability of the complete mission is synthesized from the notion of assessing the reliability of each phase separately, taking due notice of the fact that certain functions are common to all phases while others are unique to a particular phase. This approach is particularly suitable for analysis of a system whose purpose is to meet as many mission requirements as does the Mariner R.

For each phase the necessary functions are identified, and the physical equipment required to sustain them is delineated with functional, system block-diagrams. The idea of a "unit" is then introduced. This is a piece of equipment (whose complexity in terms of actual hardware is unimportant at this stage) which can be associated with a well-defined function or subfunction that has to be accomplished if the mission is to succeed exactly *according to* plan. Notice here that success may be possible in some way which does not conform exactly to this plan. This is a fact whose significance will be developed subsequently. Units are the things whose individual reliability is basic to the model. They are assumed to be "up" (functioning according to specification) or "down" (not according to specification, degree notwithstanding) according to statistical principles well known in reliability analysis. Among all units, the total combination of those up or down is defined as a "state" of the complete system.

For any phase of the mission the manner in which it is performed is called a "path." A path which deviates from the planned mission in any detail is then regarded as being imposed on the desired scheme due to the unavailability of units which are postulated as down for the phase

[1] Appendix B explains what this model entails and how it differs from other reliability estimates.

in question. Thus a path implies and is implied by a state. Once down in a given phase, it should be observed that the unit must remain down for all subsequent phases, so that paths in successive phases have a serial interaction. The combinatorial, statistical formulation of the analytical model pays attention to this fact, using the concept of a "route." This is defined as a combination of successive paths through the series of phases comprising the mission. Except where all units are always up, it is in general true that the available route, constrained by the functions omitted due to the down units, will correspond to a degraded achievement of the mission objectives. The model then enables the probability of such a degradation to be computed, using the reliability postulates of the individual units as a determining array of quantities.

The degree of accomplishment of the objectives laid down for any particular phase of the mission may vary from perfect to negligible, according to the path which applies. It is possible to associate a value (ranging from zero to one) for the degree of accomplishment, using the mission objectives as a standard of measurement, and correspondingly a value may be computed for any route which may be worth investigation. The same route, in terms of the paths which comprise it, also has a certain probability of occurrence, as noted in the foregoing argument, so that the expected value for any mission, not necessarily the intended one, may be derived from quantities which are capable of rational estimation or derivation. This value is the figure-of-merit reliability estimate.

A schematic flow chart of the study approach is given in Exhibit 1. This shows the connection between the various steps of the formulation of the model just outlined. In order to emphasize these steps each may be succinctly described as follows.

1. Note mission objectives, especially the inherent interdependence and time sequences. This suggests a special approach to the assessment.

2. Introduce and define the Phases of the mission by picking out appropriate milestones from the flight-event sequence.

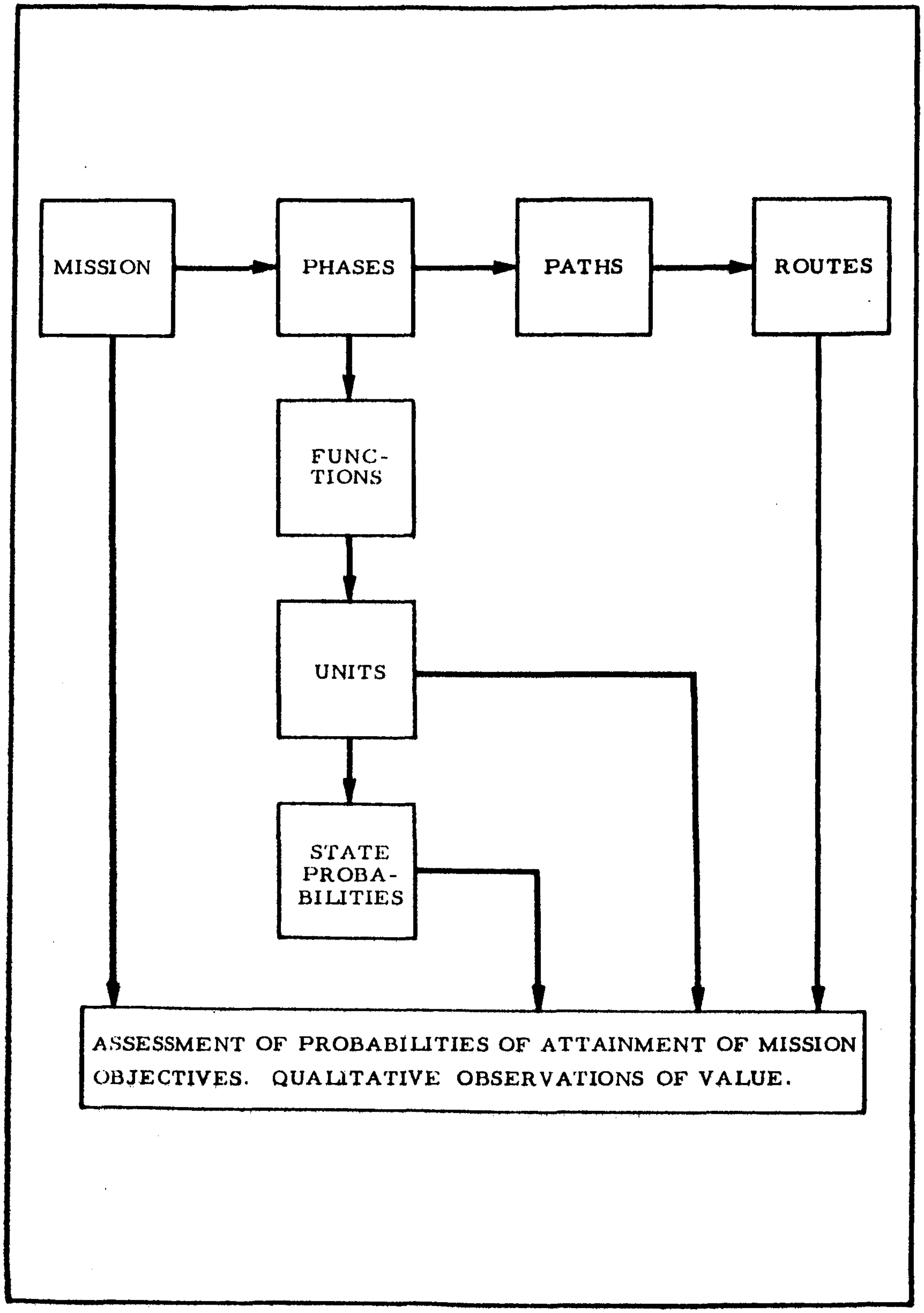

EXHIBIT 1 - SCHEMATIC OF RELIABILITY MODEL

3. Establish the essential and ancillary functions which are performed through and are characteristic of the four phases.

4. Use these functions as a basis for the system descriptions and block diagrams.

5. Combine and/or dissect the blocks of the system diagrams to make units (equipment groups) suitable for individual reliability (probability of successful performance) assignments.

6. Define the paths possible for a phase both in terms of functions available and plausible states of the units, either up or down.

7. Use the up or down combinations and configurations of units, or system states, to find the allowable paths of operation through each phase.

8. Establish routes of sequential paths through sequential phases, noting permitted and prohibited combinations on account of unit availabilities and system states.

9. Set up combinatorial probabilistic expressions of success for units, states, paths, and finally routes.

10. Compare the route success probabilities with the mission objectives.

11. Use values associated with these objectives to obtain the figure-of-merit reliability assessment.

C. Summary of Conclusions

The purpose of the work reported in this writing is to formulate the reliability model. The exercising of the model, by the introduction of numerical quantities and subsequent evaluation, is purposely excluded from the present scope of effort. Therefore, there are no quantitative conclusions concerning the expectations of success in the various Mariner R mission objectives. As concerns the model, it is pertinent to remark here that a tractable formulation has been accomplished. Moreover the model as described is flexible in that the depth of system analysis and mission performance it can accommodate is constrained only by the amount of detail which is transformed into its methodology. The principles and expressions characteristic of its formulation are invariant in spite of differences in the extent of detail adopted.

Qualitative conclusions are also pertinent to this study. They are stated later in the body of the report. It is not practicable to summarize them into a terse statement at this juncture. It is, however, worth noting that the spacecraft has capabilities sufficient for its complete, planned mission only if no equipment failures occur during the three or four months of space flight. The authors of this report consider that the on-board equipment is not likely to go through such a life span without a failure, but they are in no position to state where the significant weaknesses will appear. These things will become apparent only when the quantitative model is exercised and the results subjected to a detailed engineering appraisal.

D. Sources and Acknowledgments

The work in this study has been performed with extensive reference to one document - The JPL Mariner R Spacecraft Design Specification (SDS). This document has been used as arbiter for questions of system design and operation, but where clarification was needed or conflict of details was apparent, direct answers from JPL personnel were sought. The authors of this report warn the reader not to use it for obtaining specific design information concerning Mariner R, since errors of detail are certainly present. In terms of a methodology for a reliability model, such errors are, of course, of no significance.

The authors also wish to record their appreciation for direct information received from JPL, and to compliment the compilors and writers of the Mariner R SDS for an excellent piece of documentation.

II. APPROACH TO FORMULATION OF MODEL

A. Development of Concepts

The summary of the study approach given previously has shown in broad terms how the reliability model is to be formulated. In this section of the report these matters will be reiterated in sufficient detail that the terminology peculiar to the model may be identified with the appropriate elements of the Mariner R mission and equipment configuration.

1. Phases and Events of the Mission

The reference for this topic is fundamentally the Mariner Flight Event Sequence (MR Appendix II Revision C). Since injection is excluded from the reliability investigation, the model is based on a complete mission of four phases: acquisition, maneuver, cruise, and encounter.

a. Acquisition

This begins with separation of the spacecraft from the booster and terminates with the satisfactory stabilization of the earth-sensing servo. During this phase the significant events are the erection of the solar panels, the onset and termination of solar acquisition, the tracking of the vehicle using doppler data from the coherent transponder, and the onset and termination of earth acquisition. The time spread for these events is about eight days, on the assumption that all proceeds according to the planned sequence.

b. Maneuver

The midcourse maneuver occurs just once in the mission. It begins with the reception of data commands, which are stored for subsequent control of the impulse vector. These commands are computed at the DSIF[1] according to observations of the vehicle's actual path and attitude prior to the time allocated to the maneuver. On receipt

[1] Deep space instrumentation facility

of the initiation command, the spacecraft reorients itself against an internal reference and fires a rocket motor to correct for aiming inaccuracies and thus secure the desired approach to Venus. This phase persists for about four hours.

c. Cruise

The cruise phase which follows begins with reacquisition of the sun and earth, exactly as previously, and then persists in free trajectory and controlled attitude for several months, with the high-gain antenna directed towards earth to provide long-range telemetry.

d. Encounter

A modified program of scientific measurements is automatically begun with the encounter phase. The Venus fly-by, which constitutes the prime event during encounter, is planned to last about 67 hours, and after this time the mission is deemed to be essentially completed. Cruise is then resorted to, until such time as the communications range prohibits telemetry.

It is worth noting that there is a close (but not exact) correspondence between the "modes" of the flight event sequence as written in the Mariner R SDS and the phases used here. Small differences enable the model to be simplified and do not affect the over-all mission evaluation to any significant degree. For example, the onset of the cruise science during acquisition is ignored, as is the resumption of cruise after the encounter. Exhibit 2 shows the phases in relation to some other interesting parameters of the mission in idealized form.

This representation of phases is of course based on the normal way of conducting the mission, so that accidental events which may occur are purposely neglected at this juncture.

2. Functions Required for the Mission

a. Purpose of Functional Formulation

The complete set of things which must be performed in order for the spacecraft to complete a successful mission may be broken

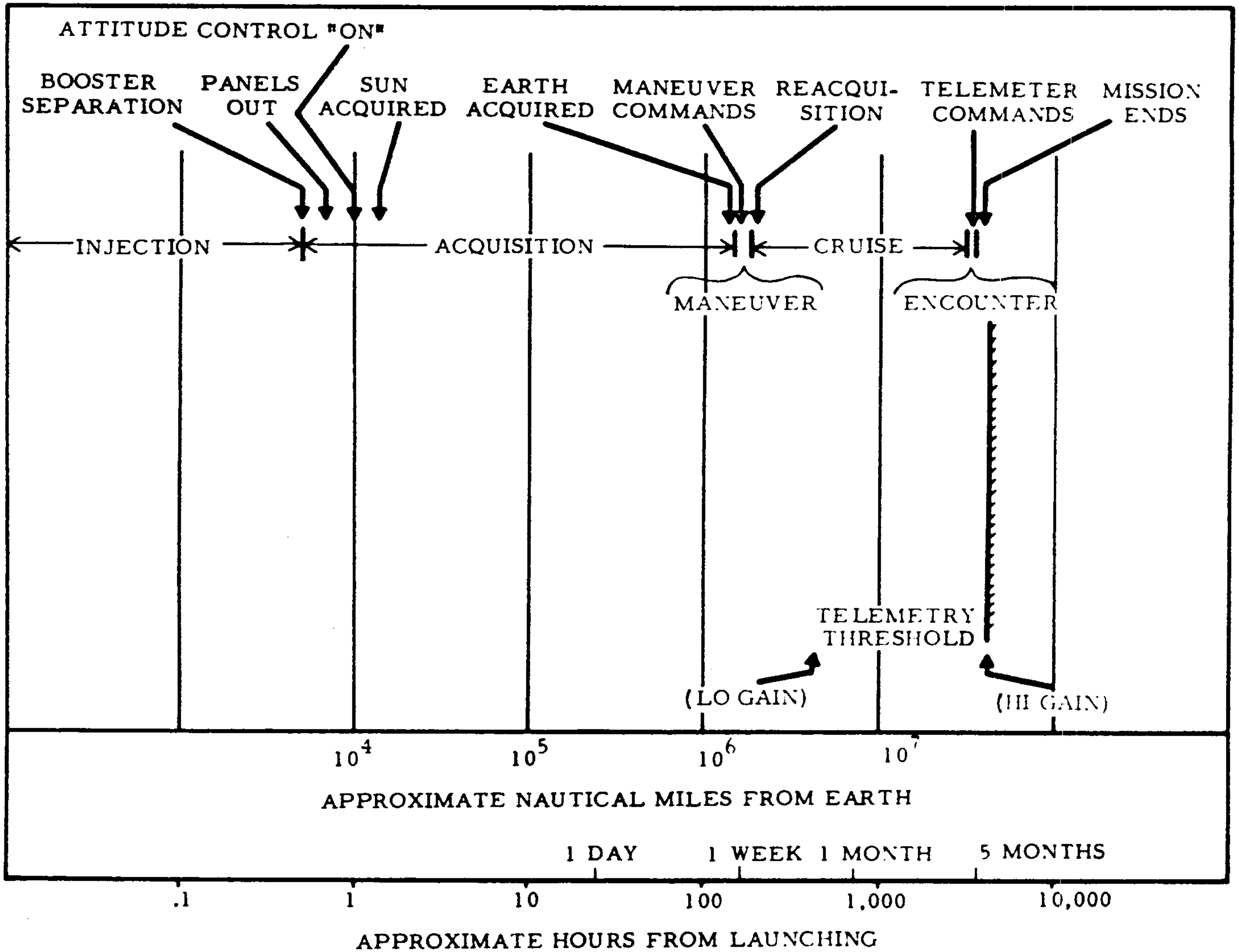

EXHIBIT 2 - PHASES AND EVENTS OF MISSION

down categorically in two essentially different ways. One way is by subsystems, and corresponds to the engineering outlook on the subject. The other way is by functions, which tends to follow an operational outlook. There is of course a degree of similarity and overlap between the two approaches. The functional model is convenient to use at this stage of the investigation since it is substantially independent of the engineering question as to how a particular function can be accomplished. It also places emphasis on the primary lines of dependence between the various functions, and the way in which this pattern of dependence alters during the successive phases of the mission.

Since details of design will subsequently be attended to on a subsystem basis under each function it is appropriate to keep the functional model as simple as is possible without omitting anything of obvious significance. With this constraint imposed, a minimal set of functions may be established as follows. The normal state, which applies to the present context, is the condition where all systems are expected to perform in accord with the planned flight sequence; that is, everything is "up" for the entire mission.

b. Definitions of Functions in Support of Mission

(1) Measure Science

(a) Measure directly six distinct classes of physical quantities.

(b) Condition the measured data into digital format.

(c) Frame data into word groups compatible with the telemetry data encoder.

(2) Measure Engineering and Encode Data

(a) Measure directly up to 53 engineering quantities characteristic of the internal working of the spacecraft. (Currently, 48 of these are assigned.)

(b) Condition the data into digital format.

(c) Commutate data words coming from science and engineering.
(d) Separately frame the science and engineering data, and signal the frame identity.
(e) Biphase modulate the resulting signal on to an audio subcarrier.
(f) Develop a pseudo-noise phase modulated subcarrier for synchronization purposes.
(g) Add the two subcarriers and route them to the L-band transponder.

(3) Command

(a) Establish local frame synchronization with the received command signal.
(b) Decode the command and route it as appropriate, either for real-time or storage.

(4) Control and Sequence

(a) Control the midcourse maneuver using stored command data and a predetermined sequence.
(b) Supply clock frequency for the power supply and all internal timing and synchronization.
(c) Switch measurement modes for science and engineering.
(d) Switch telemetry bit rate according to the program.
(e) Supply long-interval timing pulses.
(f) Provide various event signals to actuate mechanics and pyrotechnics.

(5) Supply Power

(a) Provide electrical power from a precharged battery.

(b) Convert solar radiation when available for immediate load demands and for charging the battery.

(c) Draw upon power reserve in the battery when the solar source is inadequate or unavailable.

(d) Supply electrical loads at d-c, 400 cycles per second three-phase, and 2,400 cycles per second single-phase square wave as appropriate.

(6) Control Attitude

(a) Acquire and stabilize attitude so that the roll axis is pointed at the sun.

(b) Acquire and stabilize attitude so that the high-gain antenna points to earth.

(c) Repeat the acquisition process if necessary, either in whole or part, to achieve stability in the sun-earth reference frame.

(7) Guide

(a) Align spacecraft attitude in accord with stored midcourse command data.

(b) Supply midcourse impulse in accord with stored command data.

(c) Control attitude during the rocket motor impulse.

(8) Telemeter

(a) Phase lock the L-band carrier to a received reference carrier from the DSIF if this is available; otherwise, use internal crystal frequency control.

(b) Transmit added data and synchronize subcarriers using phase modulation of the L-band carriers.

(c) Receive and demodulate the L-band carrier signals from the DSIF.

c. Interpretation of the Definitions of the Functions

The interpretation of the foregoing definitions should be guided by the notion that they are intended to be apart from system hardware configurations, even if the terminology may suggest some associations. How the system components provide the functions is a matter which will be discussed in detail later in this report. It should also be emphasized that the functions as defined relate to the normal state of the complete spacecraft; that is, everything is assumed to be capable of performing its tasks according to specification. It is therefore inappropriate to consider alternative modes of operation while interpreting the definitions. Together they describe all processes that are needed to accomplish the desired mission. Degraded states may exist where the mission can still be carried out, implying that all the processes can be effected. The difference between this case and the normal state is one of operational equipment supplying the functions. This is a matter of system and hardware performance leading directly to equipment reliability concepts.

3. Functions Associated by Phases of the Mission

In this section of the study the first stage of the formulation of the reliability model is introduced. For each of the distinct phases of the mission the functions and the implied processes will be examined. This will be done initially in the normal, or undegraded, state of the spacecraft system. Subsequently a survey of degraded states and the modes of operation then feasible will be carried out.

The eight functions are all at some time necessary to the fulfillment of the Mariner mission objectives, but through the various phases the degree of importance, and sometimes the existence, of a given function is not constant. Moreover, the functions, being mutually dependent for the most part, vary in patterns of interdependence. The identification of these patterns is important for subsequent understanding of the interfaces between the appropriate equipments and subsystems.

a. <u>Acquisition Phase</u>

In the normal state the functional set is shown in Exhibit 3. In this phase the guide and measure science functions are not used. The only independent function (that is, one on which no other function depends directly) is the performance of the engineering measurements, since the phase could be traversed without them. The balloon diagram in Exhibit 3 shows this clearly, as no arrow leaves the measure engineering balloon. Power is supplied initially from the charged battery until the solar cells become illuminated. Attitude is not controlled at the start of the phase; [1] it begins with sun-sensing and acquisition, followed almost a week later by earth acquisition, which puts the high-gain antenna in alignment for telemetry, and establishes a reference vector for the controlled maneuver. The steps of acquisition are timed from control and sequence, which also supports requirements from telemetry, such as synchronizing signals and timing pulses, and sequencing control for the various engineering measurements. Telemetry is involved so that the performance of the systems can be monitored by the DSIF. Command is used to change the high-gain antenna direction as necessary, in the event that the hinge servo has not become effective; command can also change the telemetry between the two antennas as needed.

Provision has been made for an optional command override of the earth acquisition by initiation of a controlled roll. This is to be used in the event of acquiring a wrong external body. Command backup is additionally possible to effect the unlatching of the solar panels and the initiation of the sun-acquisition mechanism. The removal of the inhibit on earth acquisition is also open to a command override. Thus both acquisition effects may be initiated at times different from those controlled by the internal sequence mechanism.

The duration of the acquisition phase is not capable of exact definition. Solar acquisition is intended to take place immediately after injection and the erection of the extended components of the spacecraft. This

[1] The allowable tumble after injection is specified, however.

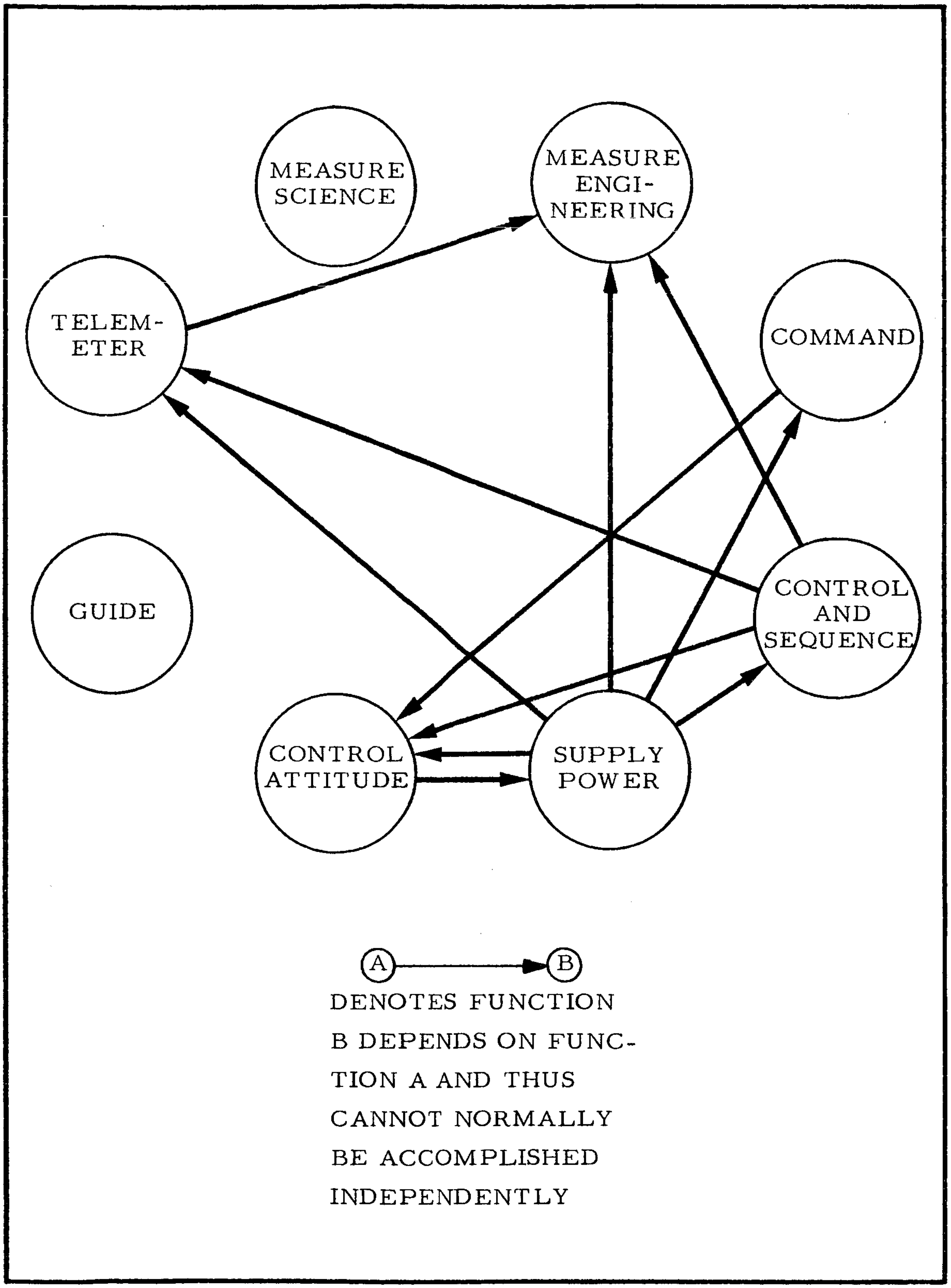

EXHIBIT 3 - FUNCTION DEPENDENCE RELATIONS - ACQUISITION PHASE

is at 1 to 1-1/2 hours after launch. Earth acquisition commences 167 hours after launch, and has a duration dependent on the success of the automatic control devices. Command of a repeat of the earth acquisition process is planned in the event of wrong outcomes of the automatic procedures. Some allowance for such an event has been made in the programmed flight-event sequence, which considers the acquisition phase to terminate 7.6 days after launch.

b. Midcourse Maneuver Phase

In this phase the purpose is to make vernier corrections to the Mariner trajectory so that it achieves the desired approach distance from Venus. Unwanted functions at this time are control attitude and measure science. The phase begins with the issuance of command data from the DSIF, which is stored for subsequent use. Engineering measurements are continued through this phase, and require the use of telemetry. Control and sequence is thus necessary to perform the synchronization and timing for this telemetry, as well as for the maneuver gyrations. The power for this phase comes in part from battery storage, since the sun position is not necessarily as desired at all times. The balloon diagram of Exhibit 4 shows the set of functional dependencies. Guide is in this case an independent member as it is the immediate objective. The success of the subsequent components of the mission profile is contingent on its accomplishment.

It should be noted that the computation (at the DSIF) of the desired correction impulse depends on precision tracking of the spacecraft through the acquisition phase. Such tracking uses doppler measurements and thus demands the availability of coherent, phase-locked radio carriers.

The time occupied by the maneuver phase is about 4 hours. The first 2-1/2 hours are needed to receive and store the commands, and to wait as necessary for the computed time of initiation of the maneuver proper. One hour is then used to run up the gyros, following which the roll turn is made in about 9 minutes. Next the pitch turn is completed after about 17 minutes, followed, after an interval, by the impulse, which lasts less than 3 minutes. Sun acquisition is thus broken for about

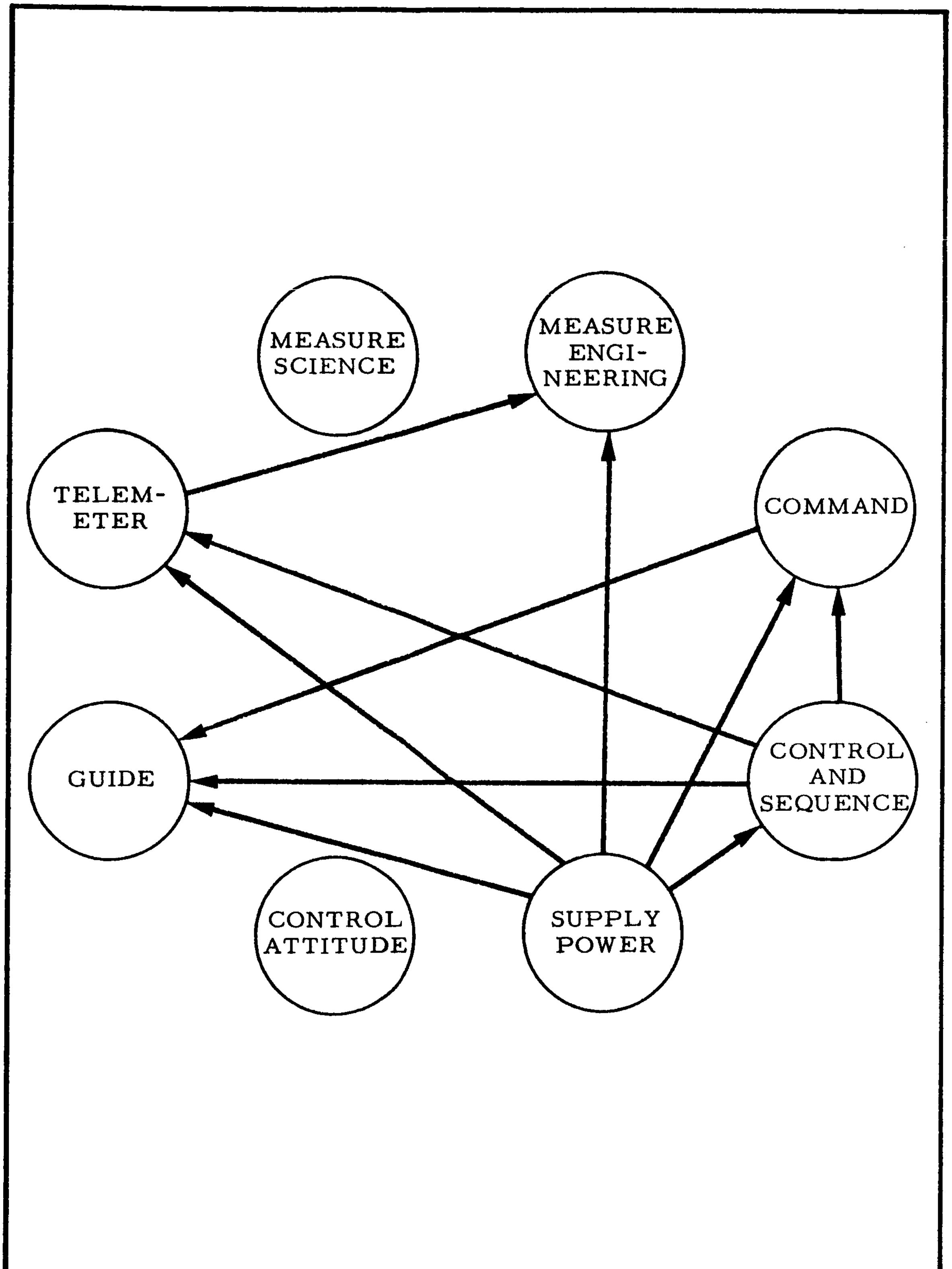

EXHIBIT 4 - FUNCTION DEPENDENCE RELATIONS - MIDCOURSE MANEUVER PHASE

26 minutes, and is expected to be restored subsequently inside 30 minutes; this acquisition is, however, regarded as a part of the cruise phase.

c. The Cruise Phase

This occurs for a brief period prior to the maneuver,[1] and endures for some months following the maneuver. During cruise, the mission objectives of scientific measurement in interplanetary space are accomplished, as well as those of measuring the internal workings of the vehicle in the space environment. Command and guide are the unused functions; the others have interrelations as shown in Exhibit 5. The power comes from the solar cells, so that vehicle attitude is involved. Attitude is also involved in the telemetering of data via the high-gain antenna, and in the orientation of the science experiments. Control and sequence is continuously required to monitor antenna hinge angle and provide clock references. The most significant thing about the cruise is the possibility of its being up to 5 months in duration, for all of which time data will be continuously telemetered. It is of incidental interest to note that the telemetry communications, which measures doppler shift by means of a radio frequency phase-lock technique, undergoes a recurrent break and remake of the lock as the various DSIF stations assume the responsibility for reception.

As noted previously, cruise is considered to begin with acquisition of the sun, and then the earth, from the orientation existing at the termination of the maneuver. The planned flight-event sequence expects these acquisitions to occur without aborts; this is in contrast to the initial acquisition of the earth following injection. Thus the command function is considered as an abnormal requirement during this phase. Accidental loss of attitude due to external causes is anticipated to be likely (with probability 0.07) at some time in the cruise phase, but recovery should be automatic if power reserves are not exceeded. Antenna switching follows automatically if the directional antenna loses its earth

[1] This fact is ignored in the adopted phase-breakdown.

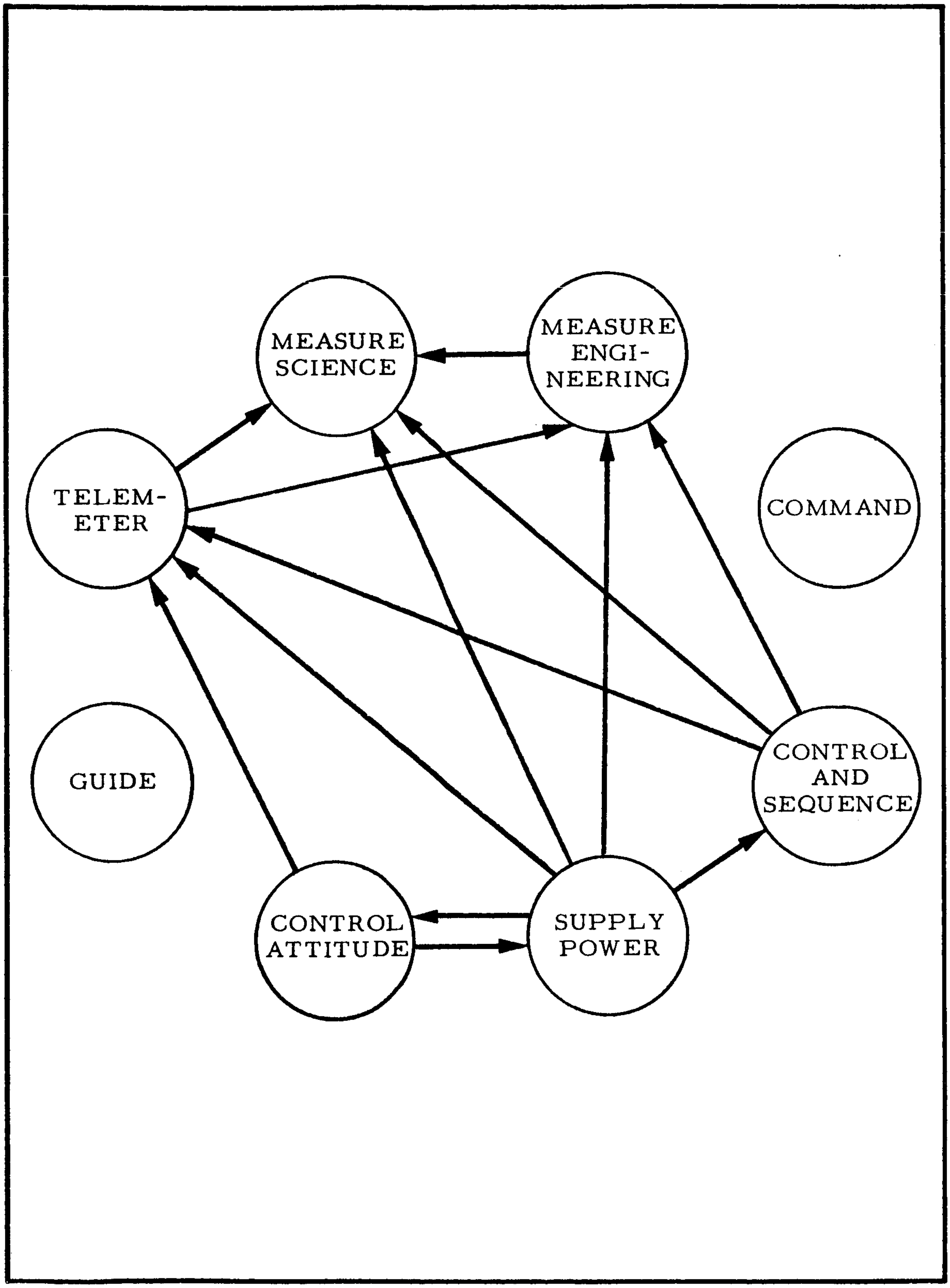

EXHIBIT 5 - FUNCTION DEPENDENCE RELATIONS - CRUISE PHASE

orientation, and the command for this may also be regarded as an abnormal requirement. Cruise terminates when, after a time programmed before launch, the encounter functions are initiated.

d. The Encounter Phase

This is essentially similar to the cruise except that the engineering measurements are suppressed so that increased sampling rates can be applied to the science measurements while near to Venus. The services of the data encoder, which is a part of the engineering measurement function, however, are needed. The radiometer experiments are also activated only at this time. Thus, as is seen in Exhibit 6, one function is not used during this phase, since guide has already served its purpose. Notice that the dependence of the Venus proximity on guide success is not in the balloon diagram, which is the result of postulating normal operation of all the functions in the present context. A notable difference between encounter and cruise is the inclusion of a command activation of the special Venus science measurements, as a programmed backup to the automatic operation. Following the encounter, the cruise mode is reinitiated by automatic control, and this event also is given a command backup. Finally, it should be noted that the ensuing cruise continues for as long as communications is practicable, and that the mission is positively terminated after this time by commanding the high-gain antenna to be directed at the sun.

Encounter is programmed to persist for 66.7 hours, and the command return to cruise will occur after this time. It is begun 10 hours before the time of closest approach to Venus.

B. Implementation of the Functions

Each of the functions noted as being substantially distinct in concept is performed by the cooperative efforts of groups of subsystem devices. Some functions depend on few systems, some on many. Moreover, the mission is not autonomous to the spacecraft, since certain functions need the ground environment systems of the DSIF for their accomplishment, as with data processing and emergency command

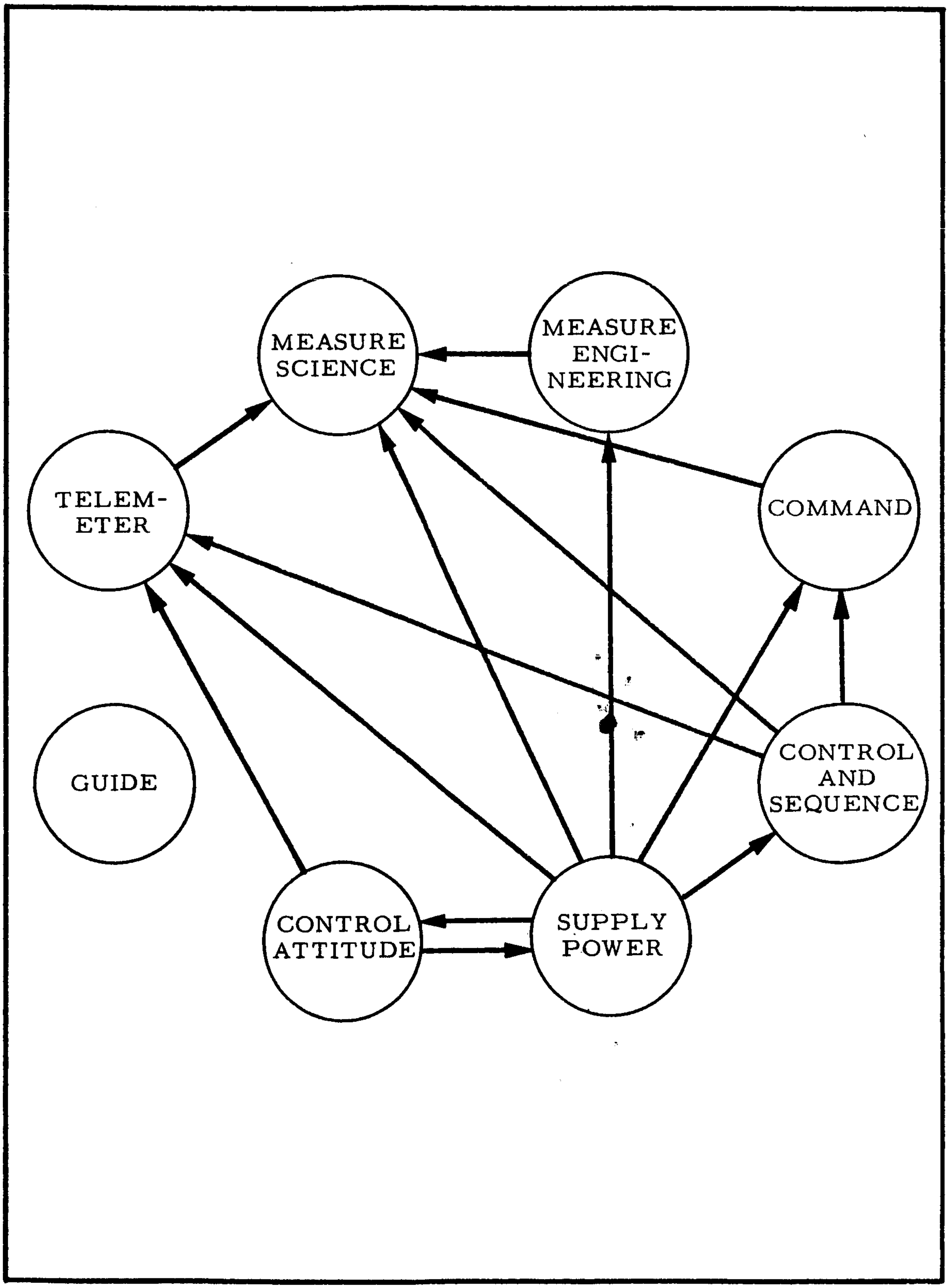

EXHIBIT 6 - FUNCTION DEPENDENCE RELATIONS - ENCOUNTER PHASE

override of some of the functions which are normally implemented automatically. System block-diagrams in this section show how the functions are implemented by the various hardware equipments. The systems themselves have been identified and named according to the Mariner R SDS. Individual working descriptions of them in a detailed sense will not be given here on account of the excellent expositions available in the JPL specifications.

In order to trace the lines of intersystem dependence that are basic to the formulation of a reliability model, it is convenient to investigate separately each of the functions to be performed. In this way the descriptions of inter-related systems which follow are kept from becoming excessively complicated, while the processes each system contributes to the functions and mission remain in evidence. Interfaces exist as shown previously in the balloon diagrams, since most functions are not independent; these interfaces are explicitly enumerated here in the system block-diagrams.

1. Science Measurements

The scope established for this investigation eliminates the inner workings of the science subsystems. For present purposes each of them may be regarded as a black box with electrical (and sometimes mechanical) inputs and outputs. The function in question then becomes a matter of switching power, sequencing events, and transforming the output data into the desired time-multiplex digitally-coded format. The necessity for securing correct vehicle position and orientation for those measurements that require controlled attitude is covered in the dependence of the science measurement function on other functions as appropriate.

The science measurements quantities taken only during the encounter with Venus are as follows:

a. Radiometer Measurements

(1)	Radiometer, 13.5 mm	Analog
(2)	Radiometer, 19 mm	Analog
(3)	Radiometer scan position	Analog

b. Infrared Measurements

(1)	IR, 8-9 microns	Analog
(2)	IR, 10-10.5 microns	Analog
(3)	IR housing temperature	Analog
(4)	IR calibration temperature	Analog

The following quantities are measured at all times except during maneuvers.

a.	Magnetometer Measurements		
	(1)	Magnetometer x	Analog
	(2)	Magnetometer y	Analog
	(3)	Magnetometer z	Analog
	(4)	Magnetometer temperature	Analog
	(5)	Magnetometer xyz scale	Digital
b.	Plasma Measurements (depends on solar orientation)		Analog
c.	Cosmic Dust Measurements		Digital
d.	Ions and Particles Measurements		
	(1)	Ions (ionization chamber)	Digital
	(2)	Particles (Geiger counter)	Digital
	(3)	Particles (Geiger counter)	Digital
	(4)	Particles (Geiger counter)	Digital
e.	Power-Sensing Measurements		Digital

Power as needed for these experiments is supplied through the scientific power switching unit (SPSU), which is essentially a group of interconnected relays. (They are specially oriented with respect to launch booster thrust.) Inputs to this switching unit come variously from DSIF Command, central computer and sequencer (CC and S), attitude control, scientific data conditioning system, and power supply. The switching ensures that the experiments are essentially independent or coordinated as is appropriate. A transformer-rectifier unit (TR) converts the 2,400 cps power to bus supplies for the various other science components.

All science measurement outputs go to the data conditioning system (DCS), which makes the analog-to-digital and digital-to-digital conversions, establishes pulse and frame times, and finally composes the science data word for the telemetry via the data encoder. The DCS also issues control signals to the SPSU.

The science measurement devices are deactivated during the mid-course maneuver by a signal from the attitude control to the SPSU. Command signals are also able to put the cruise science on (RTC 8C) or off (RTC 10) at any time. At the start of the encounter, the CC and S signals the beginning of the Venus measurements (radiometry and IR). Scan then proceeds at either of two rates according to whether the disc of Venus is in view or not. The scan reverses direction when each pass of the disc is completed. This operation is repeated subsequently by command from the DSIF, as a backup in the event that the CC and S has performed undesirably. After encounter, all systems are returned to the cruise mode, according to CC and S program backed up by a DSIF command signal, and the mission terminates when distance from the earth makes the telemetry operation impossible. Exhibit 7 shows the intersystem relations in support of the science measurements function.

The information on which this section is based is derived primarily from parts MR-4-210, 4-220A, and 4-230A of the Mariner R SDS.

2. <u>Engineering Measurements and Data Encoding</u>

The operating state and condition of the numerous systems and devices on board the spacecraft are measured by appropriate transducers and the resultant electrical quantities are telemetered to the DSIF. This engineering measurement function is distinct from the function of measuring scientific quantities except for the fact that the two functions share the final data encoding, telemetry modulation, and radio subsystems. The restricted bandwidth of the radio subsystem together with the large number of data channels dictates a time-shared data transmission scheme and, consequently, the engineering measurement function is achieved on a sampled-data basis. Pulse code modulation is employed because of its favorable signal-to-noise characteristics.

The function embraces approximately 48 engineering measurements and provides for two different data rates which means two different

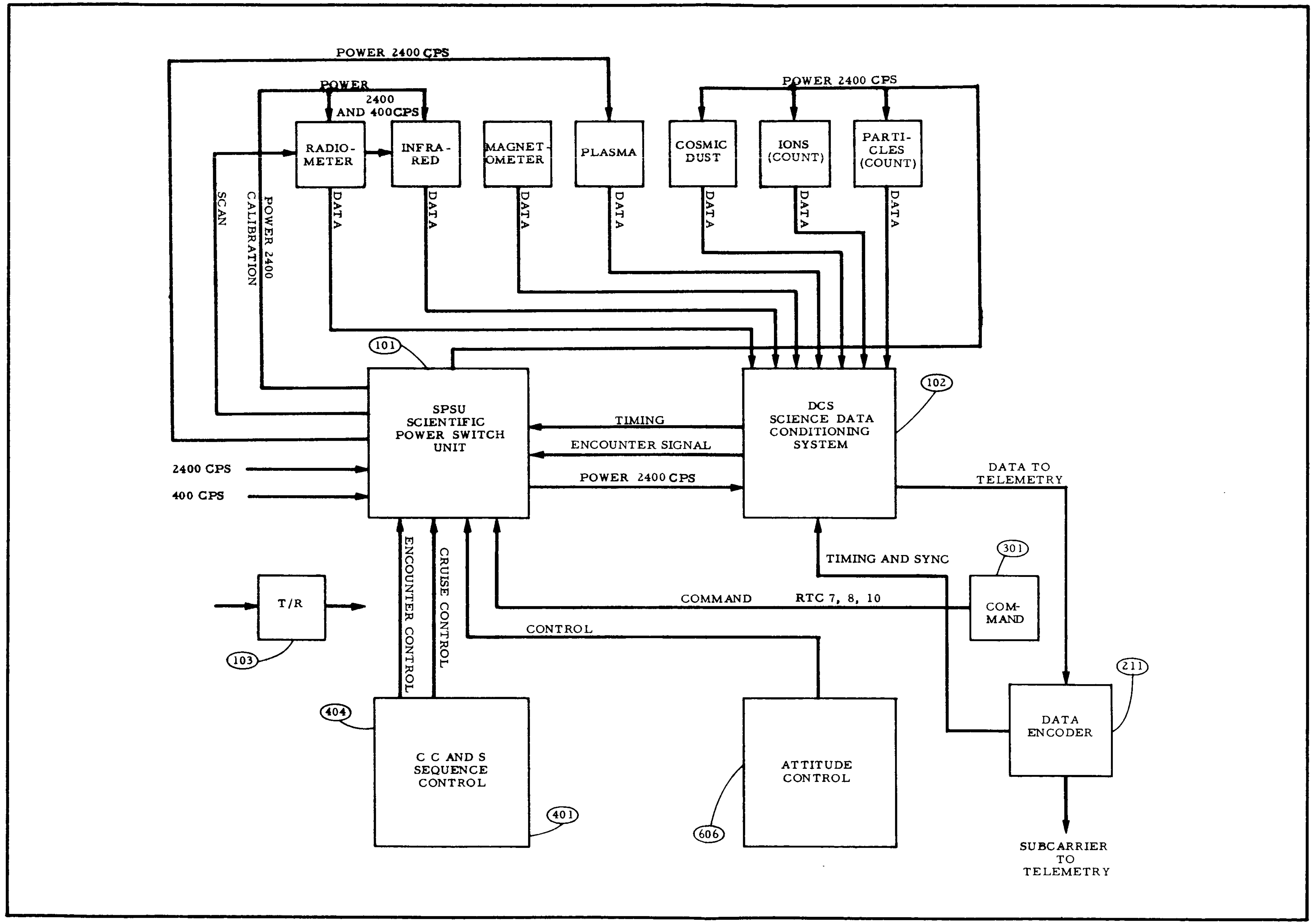

EXHIBIT 7 - FUNCTION IMPLEMENTATION - MEASURE SCIENCE

sets of sampling rates. The high-speed data rate of 33.3 bps is used during the critical first week of the mission. When the earth acquisition procedure is de-inhibited, the data rate is reduced to 8.3 bps and normally remains there for the balance of the mission. When the encounter phase occurs, the engineering measurement function is switched off for maximum utilization of scientific data transmission capacity.

a. Quantities Measured

The quantities which are measured can be categorized on the basis of the sampling rates which have been assigned to them. For a given bit rate, and considering the increased frame length with science measurements included, six distinct sampling rates can be identified. These are tabulated in terms of the period between samples for each of the two bit rates:

	33.3 bps	8.3 bps
High Rate	4.2 sec	37 sec
Medium Rate	42 sec	370 sec
Low Rate	420 sec	3,700 sec

There are 18 high-rate measurements, three medium-rate measurements, and 27 low-rate measurements. These measurements can also be grouped in accordance with the commutator deck which samples them. This has been done in Exhibit 8, which shows the commutation scheme. It can be observed from this exhibit that groups A and B constitute the high-rate quantities, group C is composed of the three medium-rate quantities, and groups D, E, and F make up the low-rate quantities. It will be further noted from the exhibit that groups C, E, and F are low-level quantities and require amplification before they are processed.

Typical signals being monitored include:

(1) High Rate - battery voltage, rate gyro outputs, optical sensor errors, earth brightness, and propellant pressure

(2) Medium Rate - L-band phase error, high-gain antenna power, and louver position

(3) Low Rate - solar panel voltages and currents, battery current, attitude control gas pressure, and a variety of temperatures throughout the spacecraft subsystems.

In addition to these analog quantities, measurements are made of a number of non-synchronous events which occur throughout the mission. These events include the receipt and execution of ground commands, actuation of on-board devices and pyrotechnics, and CC and S events.

b. Commutation

The multiplexing or commutation system is shown in simplified block diagram form in Exhibit 8 . The commutator consists of six decks of solid-state switches and associated logic to operate the switches sequentially at the selected word rate. There are ten switches and, hence, ten channels per deck. Some are assigned to synchronization words and others to subcommutation duty, leaving 53 available for data. The master counter, stepped by the basic bit rate supplied from the pseudo-noise generator in the data encoder, divides down to produce a word-rate output and a one-tenth word-rate output. The word rate steps the 20-engineering-data frame rate. At the completion of this cycle, cruise science data may be introduced, and the total frame length is increased by 24 channels. The cycle is repeated with all analog data routed through the 20 channels of decks A and B. Medium-rate subcommutation is effected through deck C which is being synchronously cycled at a one-tenth word rate. Deck C commutates the three quantities in measurement group C and routes them through one channel of deck A. In addition, deck C generates synchronous drive pulses for the low-rate programmer. This is a buffer matrix which furnishes the stepping drive for the low-rate decks D, E, and F. Since each of these decks has ten channels, the subcommutation rate is 1/10 that of deck C or 1/100 that of decks A and B. Three channels of deck C are assigned to these lower rate decks.

The first channel of deck B provides the drive for the event sequencer. When this channel is activated, one of the four event registers

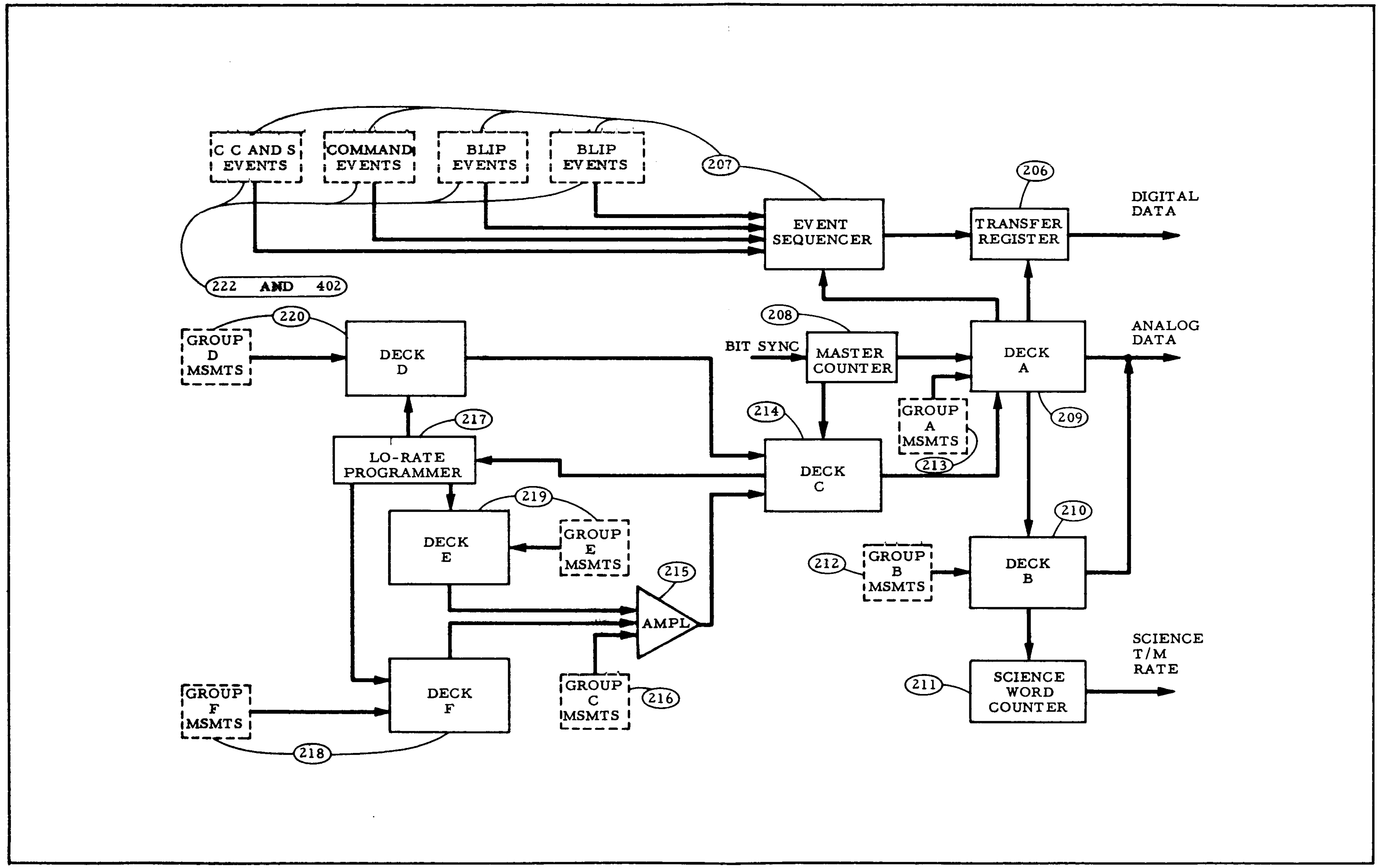

EXHIBIT 8 - FUNCTION IMPLEMENTATION - ENGINEERING MEASUREMENTS AND COMMUTATION

transfers its count to the transfer register and the contents of the transfer register are read out in serial form to the digital data line. The event sequencer empties the next event register and stores its contents until the B-O channel is again activated. Thereby, each of the four event registers is read out and emptied every fourth data frame.

c. Data Encoding System

A significant portion of this system is utilized in the conditioning and multiplexing of the engineering measurements. Commutated analog signals as well as digital event codes are produced by the engineering measurements. The science-data-conditioning system produces digital data. Before these various signals can be combined into a single channel suitable for telemetry, the analog signals must be transformed to the 7-bit-pulse-code format by an analog-to-digital converter. The commutator of the data encoder provides the timing to logically gate the quantitized engineering measurements, science data, and event codes into a single pulse-code channel in the correct sequence. This channel is shown in Exhibit 9 as the PC data line of the telemetry modulation system. This data line carries engineering data only before earth acquisition and during maneuver. From that time until the encounter phase, engineering (20 words) and science data (24 words) appear alternately on the line. During the encounter the data frame is shortened by dropping the engineering words. Exhibit 9 indicates two different sample rate commands to the science-data conditioning systems. The two rates arise from the different frame lengths, not from any change in the basic bit rate which remains at 8.3 bps after the first earth acquisition.

The information channelled over the PC data line is impressed on a data subcarrier by means of a biphase modulator. The data subcarrier is a sine wave with a frequency of 150 cps for the 8.3 bps data rate. During periods when the bit rate is increased to 33.3 bps, the data subcarrier frequency is correspondingly increased to 600 cps. The modulation consists of a 180° reversal of the subcarrier phase to distinguish between a mark and space.

d. Synchronization

The data encoding system is synchronized throughout by a coherent system of bit-rate generation. The elements of this system are displayed in Exhibit 9, which shows that the 2,400 cps clock signal from the CC and S is divided down to supply a set of coherent frequencies for the subcarriers and for a pseudo-noise (P/N) code generator. The bit rate and other sync signals are derived from the P/N generator, and hence the basic stepping rate of the commutator is also synchronized with the subcarriers. The P/N generator is a 6-bit circulating-shift register which produces a unique 63-bit code by logical addition of the first and last bits within the register. This code is characterized by a sharply peaked correlation function with minimal side lobes, and is optimum for matching and sync purposes. The code is not interleaved with the data words but is transmitted simultaneously with the data via a second subcarrier. This sync subcarrier has a frequency which is 1/4 that of the data subcarrier and a square wave amplitude 1/5 that of the data subcarrier. The P/N code is biphase modulated onto this sync subcarrier which is then linearly combined with the data subcarrier. The subcarriers, with data and sync information, are transmitted by the telemetry subsystem to the DSIF.

The prime reference for the information contained in this section is MR-4-321B.

3. Command

As noted in the general philosophy and discussion of the Mariner R mission objectives and design constraints, the need for command can enter either as part of the operational plan for the mission or as a backup to overcome some accidental failure or malfunction. In the present context, command is viewed as the former quantity, that is, a function designed into the complete system, and in this section concern is with its implementation by means of working subsystems.

Commands originate at the DSIF, and are sent to the spacecraft to secure either an immediate response or a data storage for future use.

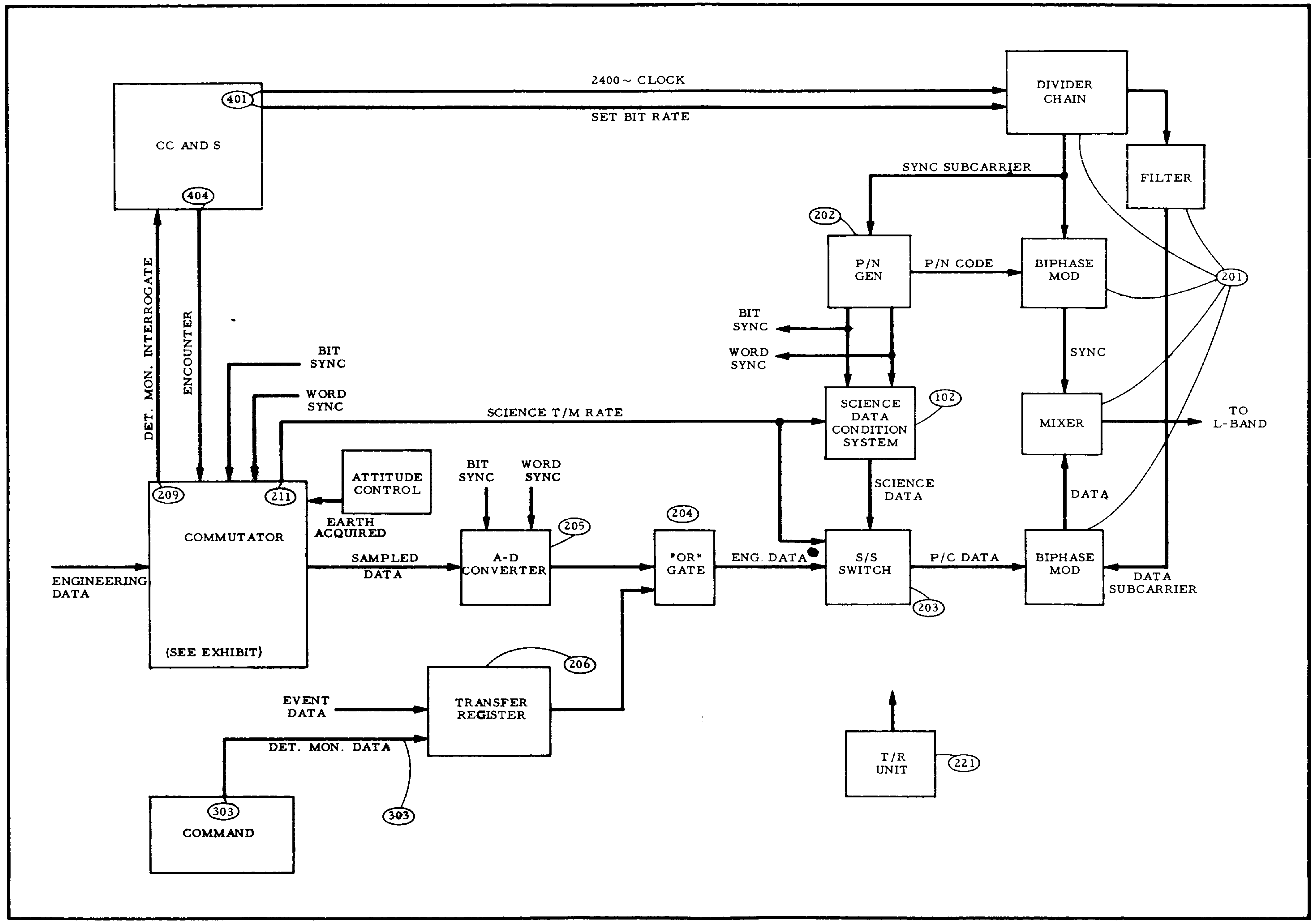

EXHIBIT 9 - FUNCTION IMPLEMENTATION - DATA ENCODER

The Mariner R vehicle therefore requires special equipment to receive and demodulate radio command signals, distinguish between immediate and delayed instructions, route them to the affected systems, and provide storage locations as needed. The processing of commands is automatically inhibited if the command subcarrier is out of phase lock. (The state of this lock is part of the telemetered data.) The description of this function is conveniently continued from here on by separating the system elements from the operational procedures.

a. Operational Procedures

Provision is made for 12 real-time commands (RTC) and three stored commands (SC). The assignment of RTC's is as follows:

RTC 1 - Roll Override.
Activates a controlled rate of roll by gas jets and gyros.

RTC 2 - CW Hinge Override.
Moves high-gain antenna an increment clockwise about hinge axis.

RTC 3 - CCW Hinge Override.
Moves high-gain antenna an increment counterclockwise about hinge axis.

RTC 4 - Command to Omni-Antenna.
Changes transmitter from high-gain antenna to omni-antenna. This conserves telemetry through maneuvers.

RTC 5 - Command to Directional Antenna.
Changes transmitter from omni- to high-gain antenna, thus undoing RTC 4.

RTC 6 - Initiate Midcourse Maneuver.
This starts the maneuver event sequence stored in the CC and S program.

RTC 7A - Command Planet Science On.
This is a backup capability to the CC and S program.

RTC 7B - Command Planet Telemetry Mode. This is a backup supplementing RTC 7A; it is normally automatic from the CC and S.

RTC 8A - Command Planet Science Off.

This undoes RTC 7A; it is a backup to the CC and S program.

RTC 8B - Command Cruise Telemetry Mode.

This undoes RTC 7B and is another backup provision.

RTC 8C - Command Cruise Science On.

RTC 9A - Command Attitude Control On.

This is an override for the control normally exercised by the CC and S during acquisition.

RTC 9B - Command Solar Panels Out.

This is a similar backup to the CC and S event occuring at injection.

RTC 10 - Command Cruise Science Off.

This is an override to the control normally made by the attitude-control earth-acquired channel.

RTC 11 - Not used.

RTC 12 - Command Removal of Inhibit to Earth Acquisition

This is an override to the control normally exercised by the CC and S on the time event sequence. This may be contrasted with RTC 1, which rolls the vehicle out of lock.

Stored commands (SC) are used only for the data needed to supply the desired impulse vector during the maneuver. They are assigned as follows:

SC 1 - Midcourse Roll Angle.

This is a coded signal containing the time over which a controlled-angular rate will be applied.

SC 2 - Midcourse Pitch Angle.

This is similar to SC 1.

SC 3 - Midcourse Velocity Increment.

This is a coded signal expressing the velocity magnitude desired, and is effected by monitoring the impulse with a pulse-integrating accelerometer.

These correction quantities are computed from observations of the doppler on the telemetry carrier and the attitude control errors from the spacecraft during the period ending after earth acquisition. The velocity and orientation measurements thus obtained are processed at the DSIF and the appropriate coordinate transformations are made.

The commands RTC 1, 2, and 3 are intended to restore order in the event of acquisition of some object other than the earth. They enable any lock in the earth-acquisition servo system to be broken. This will automatically start a new acquisition sequence provided that the inhibit is not enabled. In addition, RTC 1 and 2 allow the directional antenna to be moved so as to optimize radio communications if such is not being automatically achieved. These three commands are not scheduled as part of the flight-event sequence, and may never be needed.

Commands RTC 4 and 5, although scheduled in the event sequence, are not essential, since the antennas are changed automatically as part of the attitude-control function.

Command RTC 6 is essential to the Venus mission. There is no other way of ordering the midcourse correction essential to the desired planetary encounter.

Commands RTC 7A, 7B, 8A, 8B, and 8C are all scheduled, but only to repeat what should occur automatically.

Commands RTC 9A and 9B are intended to consolidate the capability for establishing the power-supply function during the initial stage of the flight and at such later times as may be necessary due to accidents.

Command RTC 10 is an override to the event normally initiated from the attitude control earth-acquired channel as the preparation for the maneuver is initiated.

Command RTC 8 is used to command cruise science on. It is a backup to the signal normally emitted from the earth acquisition channel when it settles. Thus the science measurement function can be entirely controlled from the DSIF in addition to its planned operation in the flight event sequence.

Command RTC 12 is intended to be used if the normal plan for earth acquisition does not occur under CC and S control These command backups are implemented so that independent circuit switching may be employed as far as this is feasible with the available relay contacts.

Commands SC 1, 2, and 3 are essential to the accomplishment of the maneuver and thus to achieving correct encounter approach distance (except in the unlikely event that injection results in a trajectory's satisfying the desired encounter without any midcourse correction).

b. System Configurations

Reception of commands is via the command antenna, a dual turnstyle and dipole combination, which feeds the receiver at 890 mc. Modulation is with two audio subcarriers that supply a synchronization channel and a command channel. Phase modulation is used, with a phase-lock, coherent demodulator that has a phase-error and voltage-controlled local oscillator. The frequency standard thereby obtained is used in the exciter for the telemetry transmitter.

After demodulation, the two subcarriers are separated in wave filters. The synchronization signal is a biphase-modulated pseudo-random 63-bit code, identical to the one synthesized in the telemetry data encoder. A correlation search finds the phase synchronism, which is then used to control local code generation in the telemetry demodulator in the correct phase. At the same time, the audio subcarrier phase is locked in. The coherent subcarrier reference thereby established is then used to coherently demodulate the command subcarrier signal, and the pseudo-noise synchronization is used as a time reference for the coded command signals. Until this lock is established, decoding of the commands is inhibited automatically. A signal to indicate successful reception of the commands is returned to the DSIF by the telemetry.

The command bits thus obtained have a word structure with a header that indicates RTC or SC, and an address that allows the correct action to begin. SC's are stored in a special register; readout is by command into the appropriate control and guidance elements. Interpretation of the stored data in terms of quantitative magnitude is done in the CC and S. RTC's are decoded in a logic that issues outputs in the form of d-c pulses or relay-contact closures, one unique to each of the 12 RTC's.

The elements and systems which comprise the command data processing arrangements are shown in Exhibit 10. The information contained in this section comes primarily from MR-4-322, with additional cross reference to MR-4-450A and MR Appendix II Revision C.

4. Control and Sequence

Controlling and sequencing the many events which the Mariner R systems must accomplish is assigned to the CC and S equipment. This function is needed through all phases of the mission; the scheduling is for the most part automatic and is set up before launch. Certain events can also be commanded as desired from the DSIF, as noted in the description of the command function. It is convenient to describe controlling and sequencing from two viewpoints, one operational and the other concerning the configuration of subsystems to achieve the desired processes.

a. Operational Procedures

Sequencing is performed from a master clock with scaling as appropriate for all intervals. Four distinct event groups may be distinguished as occurring during launch, acquisition, maneuver, cruise, and encounter. The following are the timed events with respect to launch (L), impulse (P), and encounter (E).

1.	L - 60 minutes	Input 2,400 cps power. Output timing pulses to power supply. Note that the 2,400 cps is a nominal value until the timing pulses are established.
2.	L + 44 minutes	Relay battery power to unfold solar panels.
3.	L + 60 minutes	Switch power to attitude control, starting sun attitude acquisition.
4.	L + 167 hours	De-inhibit earth acquisition and change to low telemetry rate.

This completes the launch acquisition phase. If any acquisition has not been successfully accomplished, it may be repeated by command, and a new cycle will follow under the control of the CC and S. Events 2, 3, and 4 have a command backup available.

5.	L + 180 hours (approx.)	Input stored commands for guidance
6.	L + 16.7 hours L + 33.3 hours etc.	First and subsequent cycles of antenna hinge angle updating by relay battery power. This is repeated throughout the mission. Relay also activates science calibration at each event.
7.	P	Input maneuver command. Output signal of relay battery power to gyros and accelerometer, initiating runup.
8.	P + 60 minutes	Output relay battery power signals to inhibit earth sensor, set roll polarity, attach gyro capacitors, and start roll turn.
9.	P + 60 minutes	Output relay battery power signal to stop roll. The roll occurs at a controlled rate, and the correct amount is obtained from the roll duration, a stored command quantity in the CC and S.
10.	P + 72 minutes	Output relay battery power for pitch command, set polarity, connect gyro capacitors, inhibit sun sensor and yaw error controls, and start autopilot.
11.	P + 72+ minutes	Output relay battery power to stop pitch turn. Amount is controlled as with the roll above, from CC and S stored time.
12.	P + 94 minutes	Output relay battery power to start rocket motor and input pulse train from accelerometer.
13.	P + 94+ minutes	Output relay to stop motor. Velocity desired is a stored command quantity in CC and S, compared with accelerometer reading of velocity achieved.
14.	P + 98 minutes	Output relays to stop accelerometer and autopilot. Start search rolls on pitch and yaw. This restores sun acquisition.

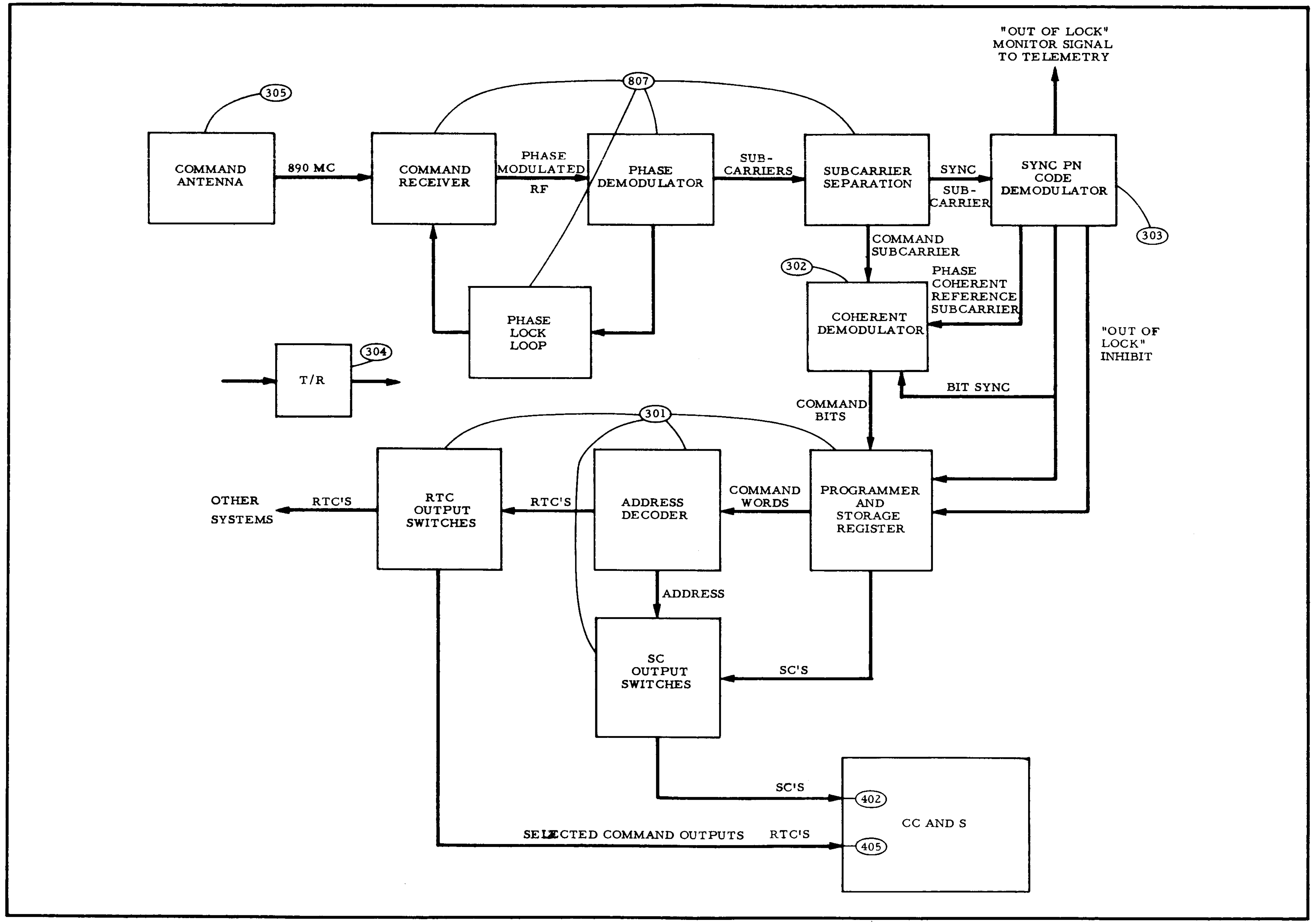

EXHIBIT 10 - FUNCTION IMPLEMENTATION - COMMAND

15. P + 200 minutes Output relay to de-inhibit earth acquisition.

The events 5 through 14 above constitute the maneuver phase. It cannot be repeated. The flight now continues on cruise mode until 10 hours before encounter closest approach while the CC and S provides the 16.7-hour cyclics.

16. E - 10 hours Output relay battery power to start encounter science telemetry.

17. E + 56.7 hours Output relay to stop encounter telemetry and revert to cruise.

These encounter events are repeated by scheduled commands after their control from the CC and S. The command overrides are, however, effected (at the component level) via the CC and S even though the latter does not initiate them.

As an addition to the specific events controlled according to the sequence just described, the CC and S is needed to function continuously for generating clock pulses which are used in the data encoder system for all telemetry. This is needed at all times. It also generates, as outputs to the telemetry, blips which are counted to affirm that certain events have occurred, so that contingent events may be suitably constrained. Typical events on injection consist of unlatching catches, firing explosive bolts, and closing relays; during maneuver, they are exemplified by valves and pyrotechnics.

b. System Implementation

The elements and systems involved in the control and sequence function are shown in Exhibit 11. The heart of the CC and S itself is a set of relays which initiate or terminate events, either by contact closure or by a momentary impulse of battery power. These relays are controlled from the preset counters and scalers which determine the correct event times and sequences, using a master clock as the fundamental reference. A ground support inhibit input is used during the countdown so that earth and vehicle times are initially synchronized. Separate counters are used to keep track of the acquisition, maneuver, and encounter events and to control the logic accordingly. Still another counter is used especially to reckon the accumulated impulses from the accelerometer during maneuver. In addition, the storage of the maneuver command data is effected in a special register used only for this purpose.

The facts pertinent to this section come primarily from MR-4-450A, with additional cross reference to MR-4-322 and MR Appendix II Revision C.

5. Power Supply

A reliable power supply is obviously of paramount importance to the Mariner R spacecraft. Electrical power is needed through all phases of the mission in order to drive both electronic and electromechanical devices. Since the load demands vary markedly, according to which events are in progress, regulation of the bus voltages is required, and means of accommodating high instantaneous-peak loads must be supplied. Some of the Mariner R subsystems use power supply voltages as a frequency standard for event timing and synchronizing, which places a further imposition on the supply: that of accurate frequency regulation and maintenance of a specified waveform.[1]

The basic form of electrical supply is at d-c, from a combined load-sharing arrangement of solar cells and a rechargeable storage battery. Some loads are supplied directly with d-c, but the majority of the electronic systems consume a-c, either sinusoidal (for servo motors and gyros) or square wave, which is particularly useful for efficient rectification to subsidiary d-c bus supplies in the electronic devices and for digital frequency reference.

Reference to Exhibit 12 shows schematically the separate units and subsystems involved in the supply of power.

For the d-c, the normal function, which applies during cruise and encounter, is for the solar cells to supply the power to the load, and to keep the battery charged via the power switch, logic, and oscillator unit. When the solar cell output voltage is inadequate, due to wrong solar

[1] As noted elsewhere, this is not always an essential requirement.

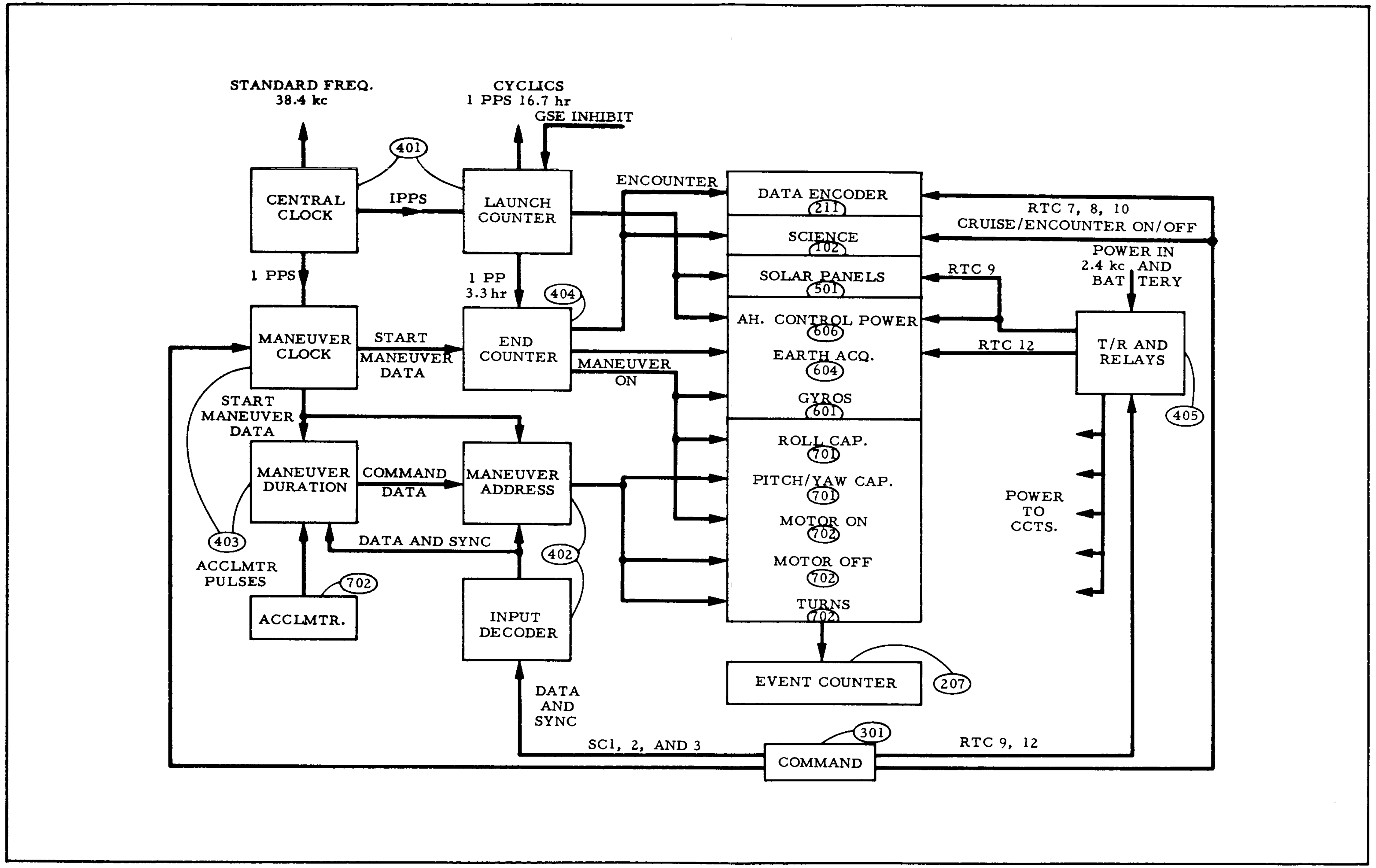

EXHIBIT 11 - FUNCTION IMPLEMENTATION - CONTROL AND SEQUENCE

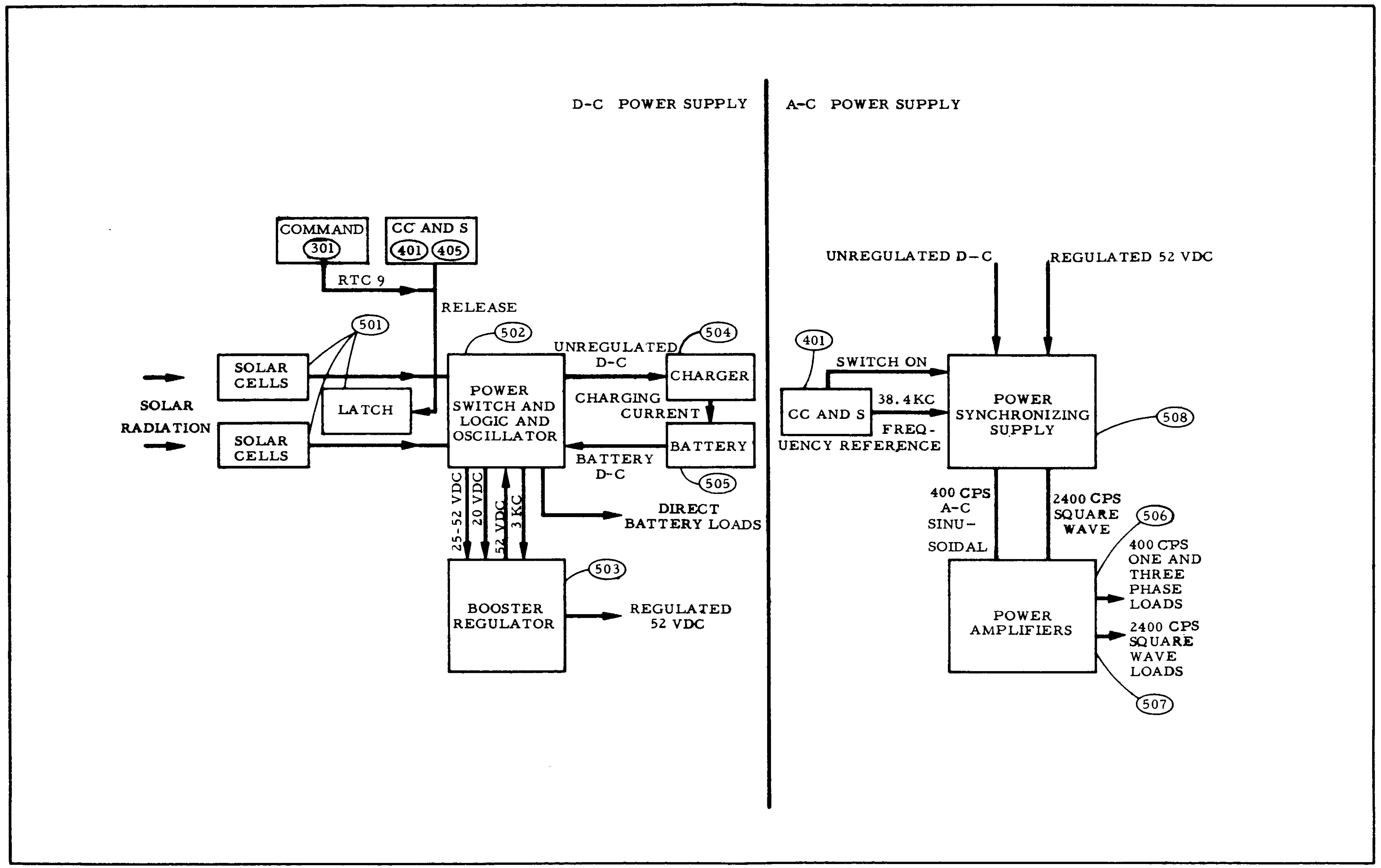

EXHIBIT 12 - FUNCTION IMPLEMENTATION - POWER SUPPLY

orientation, the battery temporarily supplies the balance of the power. Some loads are taken directly from the battery, as with the pyrotechnic fuses and the switching relays. These have high peak demands which only the battery itself can sustain. The battery is also the source for certain control pulses generated by relay contacts.

Apart from the needs of the power switch unit, the drain on the boosted and regulated 52-voltage bus is due entirely to the a-c supply inverters. The booster-regulator itself uses a subsidiary 3-kilocycle supply that comes from a special oscillator in the logic unit.

To provide a-c, inversion is effected in the power synchronization supply unit, using a reference frequency of 38.4 kilocycles from the CC and S. Ultimately this is a clock reference. The inputs are 25- to 52-volt d-c and 52-volt d-c from the power switch logic and the booster regulator. Outputs at 400-cps, three-phase sinusoidal, and 2,400-cps square wave, both clock referenced, go to dual power amplifiers, which use the 52-volt d-c bus as a primary source. The power amplifiers drive the motor loads directly and also supply a group of transformer/ rectifier units (T/R) which feed the various electronics devices. Loads are assigned as follows: three-phase gyros, single-phase antenna hinge, and single-phase science radiometer scanner, all 400 cps. Transformer/rectifier units to supply electronic systems (from the 2,400 cps square wave source) are: radio transmitter/receiver, data encoder, command decoder, attitude control, CC and S, and science experiments.

Although these a-c supplies are normally synchronized to the CC and S clock, a degraded mode of operation at nominal but unregulated frequencies[1] is possible if the CC and S input is removed.

The possibility of unscheduled demands on the power supplies exists in the event of accidental loss of the correct cruise attitude in the vehicle. This will degrade the solar input and thus place a temporary load increase on the battery. At the same time, demands on the supply will increase as the attitude systems go into action to correct the

[1] 360 cps and 2, 150 cps.

disturbances. This event has been anticipated in the Mariner R design by specification of power reserved to cope with two such accidental 15-minute periods during the cruise.

The information used in this section comes from MR-4-460A.

6. Control of Attitude

The coasting attitude control, as indicated by its name, maintains control over the attitude of the spacecraft except during powered phases of the mission. The spacecraft axes, conventionally denoted as roll, pitch and yaw, have been defined relative to the structure in such a manner that they bear a simple coordinate relationship to the on-board instrumentation and propulsion. The system configuration which provides the attitude control function is illustrated in Exhibit 13. This system serves to establish and maintain a desired orientation of the spacecraft axes with respect to selected references. Two sets of references are used for the Mariner R mission, one external and one internal.

The external references are the sun and earth. For the first week of the mission following injection only the sun reference is used, and the pitch-yaw plane is established normal to the sun-probe line. The sun is acquired by applying torques about the pitch and yaw axes in accordance with signals from optical sun sensors mounted on board. Secondary sun sensors are arrayed to view the sun from any position and primary sensors acquire the sun when it is within 45° of the roll axis. Logic within the attitude control system interprets the signals from the sun-sensor array and drives the spacecraft to a single stable null with the roll axis pointing at the sun to an accuracy of $\pm$ 1 degree. An additional sensor, with a 2-1/2-degree field, signals acquisition of the sun and shuts down the gyros which have been furnishing the control damping. During the balance of the first week after sun acquisition the orientation about the roll axis remains uncontrolled, and control about the pitch and yaw axes is damped by lead compensation.

Earth acquisition is inhibited during the first week after injection because the earth sensor cannot function properly until the earth brightness and size are reduced to tolerable levels. In addition, the delay

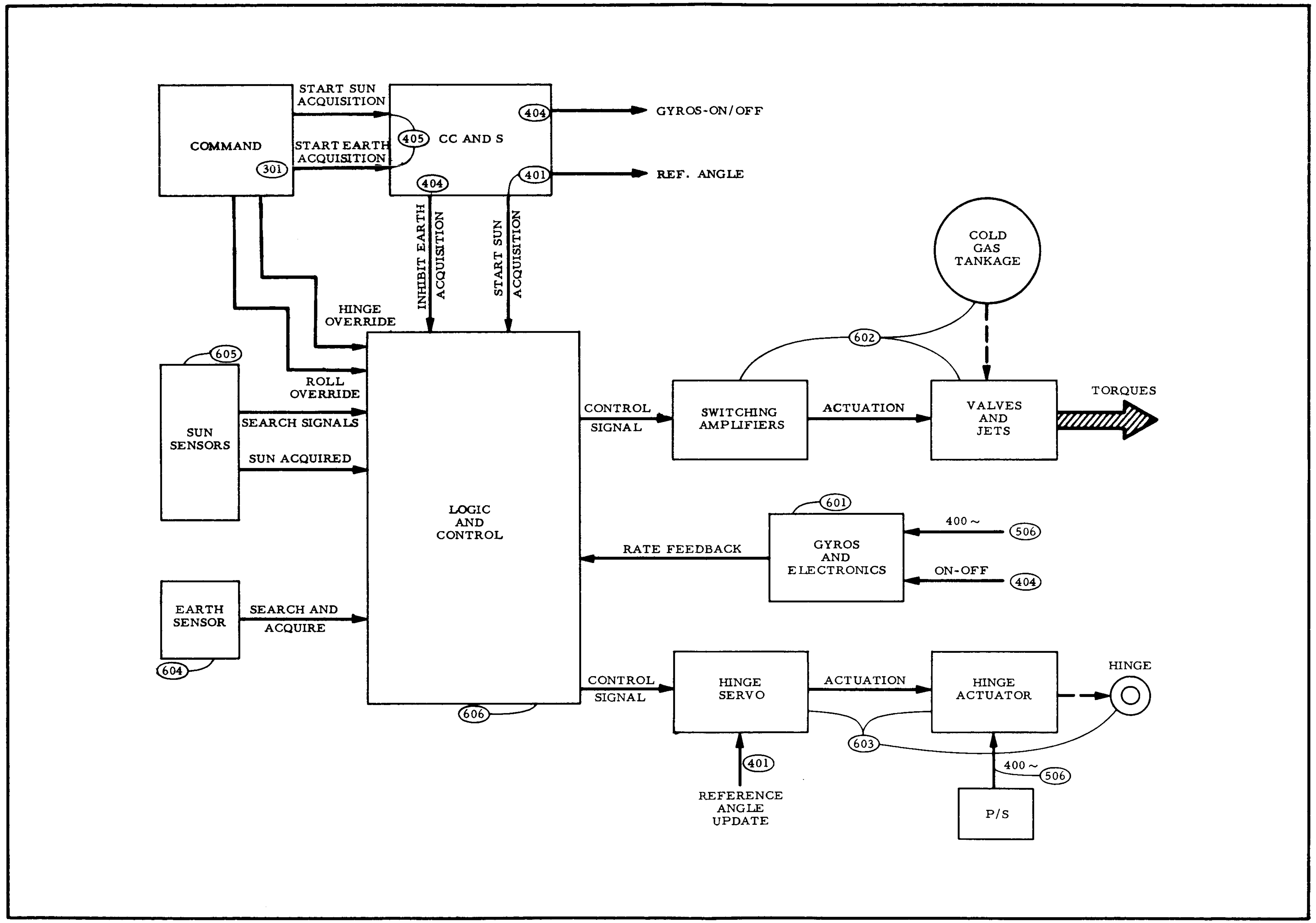

EXHIBIT 13 - FUNCTION IMPLEMENTATION - ATTITUDE CONTROL

permits the separation between the spacecraft and launch vehicle to build up, thus reducing the probability that the latter will be acquired as a false target. Earth acquisition is de-inhibited by command from the CC and S, and a ground command override is available. One of the prime motives for earth acquisition is the pointing of a high-gain telemetry antenna toward the DSIF. Accordingly, the earth acquisition function involves not only the orientation of the spacecraft about the roll axis but also the control of an antenna hinge angle. The hinge is a single-degree-of-freedom device capable of rotating the antenna in a plane through the roll axis. Earth acquisition control is of the on-off type. The acquisition procedure consists simply in commanding a fixed roll rate which is maintained until an optical sensor views the earth within its 2- by 5-degree field at which time a relay signal checks the roll rotation and activates the "earth acquired" channel. The antenna hinge angle is controlled by a servo. When the "earth acquired" channel is activated, roll-torque and hinge-angle servo operation are controlled by signals from the earth sensor so that acquisition will be sustained. The hinge servo also has a periodically updated memory of its stable position, which acts as a reference for the servo during the initial attempts at earth acquisition, whenever this reference may be needed. Damping of the roll rotation is provided by the roll gyro during the acquisition procedure; however, when the "earth acquired" channel is energized, damping for the tracking mode is furnished by lead compensation, and the gyro is de-energized.

Torques about the three principal axes are provided by cold gas expulsion from fixed nozzles mounted on the spacecraft. Valves that admit the propellant to the jets are the on-off type, allowing a limit-cycle control to be maintained. The hinge is driven by a single phase, 400 cps actuator. A ground command can reinitiate the earth acquisition procedure in the event that a false target has been acquired. A non-catastrophic collision can cause the loss of the sun or the earth, or both; the reacquisition of the targets is accomplished automatically by cycling the system through whatever portion of the procedure is necessary.

This taxes the reserve of cold gas, and provision has been made for only two such recoveries.

When the midcourse maneuver is commanded, parts of the coasting attitude control are utilized to orient the spacecraft so that the impulse from the midcourse propulsion system will be correctly vectored. This reorientation of the vehicle attitude is accomplished with respect to a set of internal references which are provided by the gyros operating in the position, rather than the rate, mode. (The gyro capacitors are switched in for this purpose.) The optical sensors are necessarily deactivated during this phase and the sun-earth reference system is ignored. The rotation torques are provided by the cold-gas jets and the attitude-control logic uses stored commands from the CC and S to position the spacecraft axes with respect to the fixed coordinate system maintained by the gyros. These rotary movements precede the actual midcourse maneuver and consist of a roll rotation followed by a rotation about the pitch axis. The roll rotation brings the pitch axis normal to the plane of the roll axis and the desired direction of impulse. The subsequent pitch rotation aligns the roll axis with the desired impulse vector direction. During the powered phase of the midcourse maneuver the coasting attitude control function is not effective, and an autopilot controls the spacecraft attitude. When midcourse propulsion is terminated, the gyros are restored to rate mode and the sun-earth acquisition cycle is again initiated. The coasting attitude control maintains orientation with respect to these external references for the balance of the mission.

The information used to compile this section comes from MR-4-410A.

7. Guidance

The guidance function satisfies the requirement of a near-miss of the planet Venus by correcting, at least to some extent, for initial errors in trajectory and velocity introduced in the launch and injection phases. The correction consists of the application of thrust from a rocket motor aligned with the roll axis of the spacecraft. For the correction to be effective, the thrust vector must pass through the vehicle center of gravity, the impulse must be carefully metered, and the roll axis must have been properly prepositioned. This last requirement is fulfilled by some of the attitude control components prior to the impulse, as noted previously. The function is implemented by the system configuration depicted in Exhibit 14.

The midcourse propulsion is furnished by a motor using anhydrous hydrazine which is stored on board in a tank pressurized with nitrogen. Only two signals from the CC and S are necessary for the propulsion control. The start signal operates three explosively controlled valves which admit fuel to the motor, an ignition catalyst to the motor, and nitrogen pressurization to the fuel storage. The stop signal operates two explosively controlled valves which check the pressurization action and stop the fuel flow to the motor. The start signal is given a preset time after the command to initiate the maneuver. This delay allows the attitude control to preposition the roll axis. The stop signal is derived by integrating the pulses from a pulse-rebalanced accelerometer which effectively meters the total impulse. The accelerometer is used only during this powered phase of the mission.

Maintaining the thrust vector through the spacecraft center of gravity is an attitude control function, but this is not provided by the normal coasting attitude control. A set of jet vanes is actuated by an autopilot to apply control torques during the propulsive maneuver. The vanes are controlled by position and rate signals from the gyro references, and the control function is clearly a matter of maintaining a fixed attitude throughout the powered phase of the mission.

The guidance function, as supplied by the midcourse maneuver is a one-shot operation and cannot be repeated. The cruise science functions are disabled during the maneuver, and engineering quantities are telemetered via the omni-antenna.

Information for this section has been derived from MR-4-420, 4-430, and parts of 4-410A.

8. Telemetry

This subsystem is shown in block-diagram form in Exhibit 15. The most important attribute of the telemetry radio transponder is its capability of operating coherently with a signal transmitted from the DSIF. It can also operate in a non-coherent mode with the carrier frequency established by a crystal oscillator contained within the system.

Exhibit 15 shows this oscillator and an associated switch which gates its output to the carrier line. Considering this non-coherent operating mode, it can be seen that the 20-megacycle carrier is phase modulated with the mixed telemetry subcarriers from the data encoder. The phase deviation is expanded by frequency multiplication techniques which translate the carrier to 960 megacycles. Two stages of power amplification bring the level up to three watts for transmission. Two antenna systems are available. When the spacecraft is not fully attitude controlled, i.e., when the earth is not acquired, a quasi-omnidirectional antenna is used. The high-gain characteristics of a parabolic directional antenna can be taken advantage of whenever the spacecraft is oriented with this antenna pointed toward the earth. A maximum gain variation of about 20 decibels exists between the different antennas. Switching between the antennas is accomplished by energizing the filament supply to the r-f amplifier associated with the desired antenna. Switching commands are automatically supplied, but ground commands for this function are also available.

The coherent operating mode utilizes the same transmitting system except that the fixed oscillator is gated out and a voltage-controlled oscillator (VCO) is used to establish carrier frequency. Phase-lock techniques are employed to control the VCO. A DSIF signal is received by the command receiver which develops a 10-megacycle/second intermediate frequency. The VCO provides the mixing frequencies for the receiver and is driven to coherence with the incoming signal by the action of the phase-lock loop. For AGC purposes another phase detection is performed on the second i-f strip and a frequency derived from the VCO but shifted in quadrature with it. This detector signals coherence by a maximum output and it is this AGC voltage which switches the transponder to the control of the VCO. This voltage also serves as the normal AGC control for the command-receiver i-f strips.

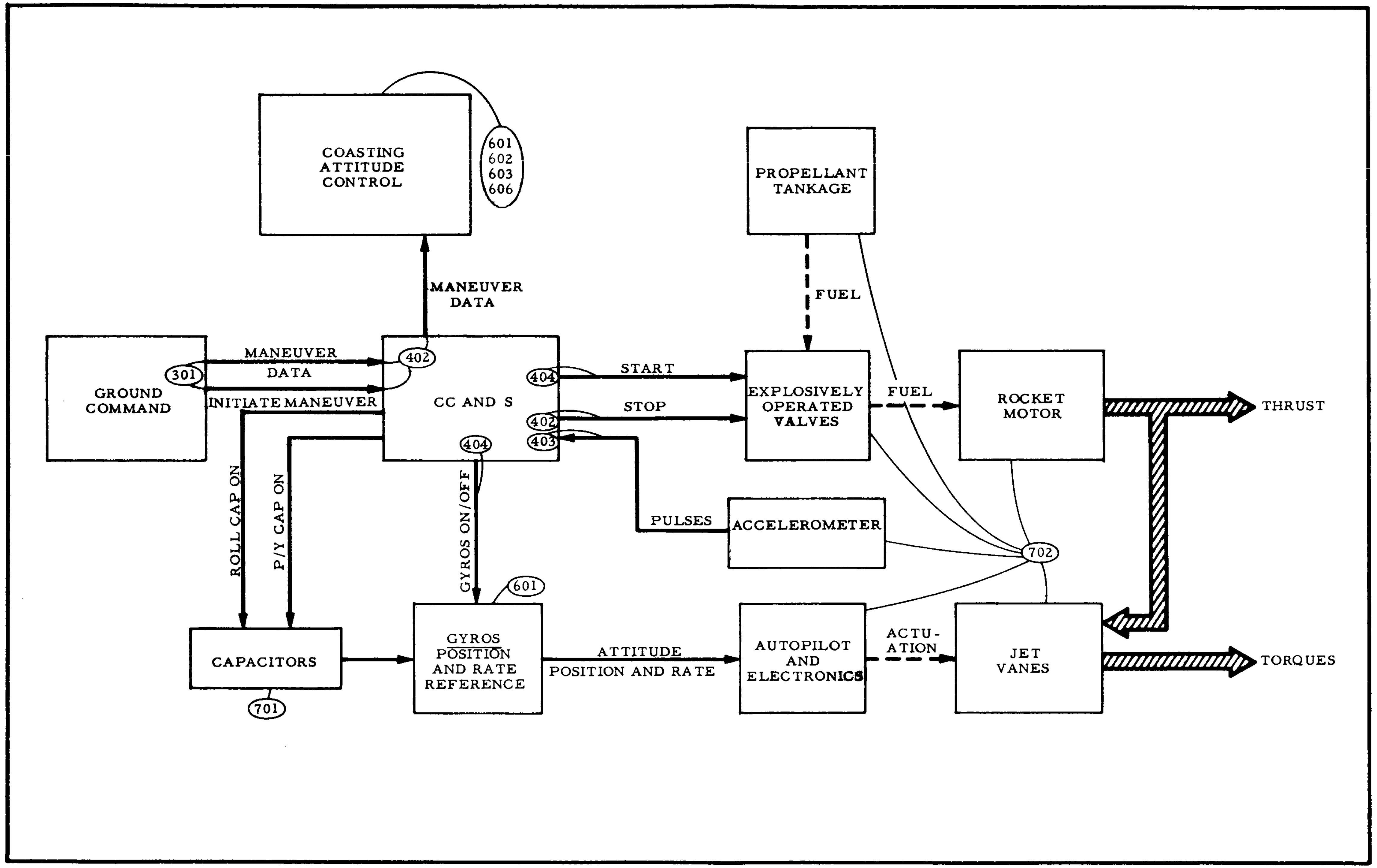

EXHIBIT 14 - FUNCTION IMPLEMENTATION - GUIDANCE

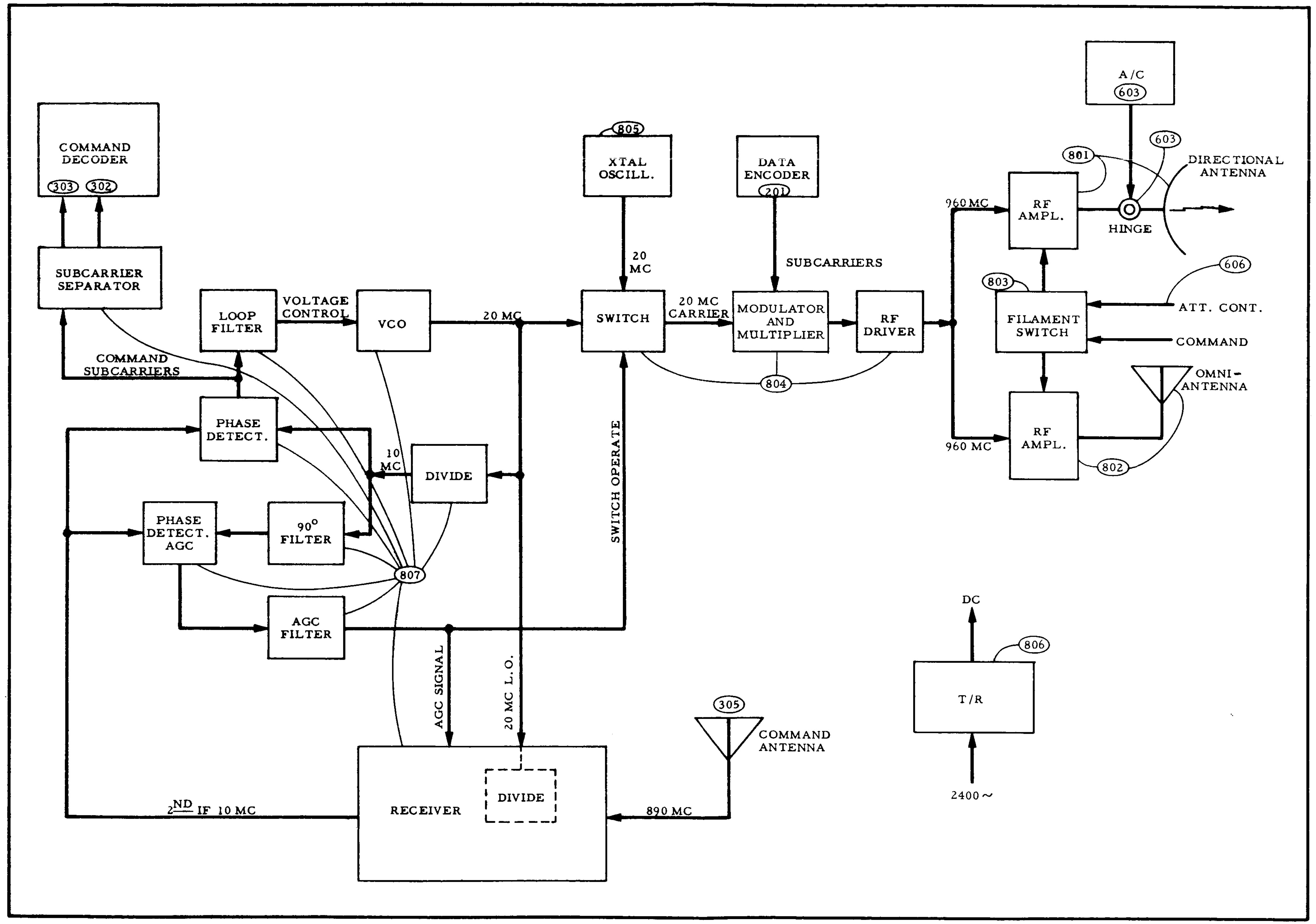

EXHIBIT 15 - FUNCTION IMPLEMENTATION - TELEMETRY

The coherent operating mode serves a number of functions. It permits narrow band operation with good noise rejection. The phase detector output not only controls the VCO, but also furnishes the demodulated command subcarriers. Finally, and of greatest importance, the phase-lock system provides doppler velocity and thus tracking information to the DSIF.

Material for this section comes from MR-4-320.

C. Further Concepts Used in the Model

1. Units for Reliability Analysis

At this point in the investigation of the Mariner R, the relationships between the functions implicit in the mission and the equipment systems which perform these functions have been described in detail. It is obvious that there is a close connection between the reliability of the equipment and the degree of success expected in the performance of functions. The present purpose is to place this connection on a rational basis with the ultimate intention of making an analytical development. This is done by first introducing the concept of a "unit," a quantity whose individual reliability becomes directly a parameter or variable in the combinatorial expressions which constitute the analytical model.

A unit in the special sense adopted here is a piece of equipment, or a combination of equipments (or subsystems, as is appropriate from the system design specification) selected so that it has as far as is possible a unique place in the hierarchy of processes involved in the various necessary functions.

How the grouping or partitioning needed to define units is done will be made clear subsequently. For ease of comprehension and reference, the selections used in this study have been tagged on the function-implementation block diagrams of the previous section. They have also been defined in terms of the component identification and nomenclature used in the Mariner R SDS, according to listings which are given later.

2. System and Unit States

The next important concept used in the formulation of the model is the notion of a string of units in series, such that the probability of success for the entire (nonredundant) string is obtained by multiplying the individual unit probabilities. The probabilities in question apply to the issue of a unit being up or down. For the entire string, the extant configuration of "upness" or "downness" is known as a "state" of the system or subsystem in question. For any conceivable state, a probability of its occurrence, computed from the individual unit reliabilities, exists.

3. Paths and Routes

For each phase of the Mariner R mission, certain functions, as noted previously, are intended to be accomplished. The actual way in which they are accomplished, measured in operational terms, is known as the "path" through the given phase. There is then an association, which is discussed at length later in this report, between a path (operational quantity) and a state (equipment or system quantity). This association is fundamental to the formulation of the model, since it allows for the assessment of reliability to be extended not only to missions which are successful, or normal in terms of the specification, but also to degraded missions, where failures and accidents are involved.

Just as a path belongs to a phase, and many paths are possible and worthy of consideration for each phase, so a succession of paths, one to each phase in serial array, combine to form a "route." A mission is thus characterized by the route which is traced. One such route is normal, where all goes according to plan, while a variety of other routes lead to other possible missions, which are in general degraded from the ideal.

The probabilistic quantities capable of being derived for each path can thus be merged, with certain restrictions, so as to form the probability for the success of any route of interest. The restrictions, and the notion of routes of interest, are discussed in detail in the section of this report describing the procedure for using the model.

The adoption of the route concept in the approach to the present reliability assessment is expedient due to the serial nature of the Mariner R mission. The experimental data accumulated at the later stages of the mission is of no less importance than the data acquired earlier. This is in contrast to some other space experiments where data acquired later serves only to corroborate that collected earlier, due, for example, to repeated passage of the same orbit. It is also notable that the long period of cruise of the Mariner R mission takes the vehicle through new regions of space continuously, so that all data acquired during this phase is in some sense new and the total collected value may be considered to increase linearly with elapsed time.

These points show how the concept of "value" is naturally a part of the desired model formulation. Values can be assigned to individual phases of the mission, as is appropriate to the subsequent mathematical development, on account of the distinct outcomes of these phases. Realistic outcomes, whose probabilities of occurrence can be estimated by exercising the analytical model, can be compared with the desired outcomes of complete achievement for all the mission objectives.

III. MATHEMATICAL FORMULATION

A. Some Necessary Assumptions

This section of the report completes the development of the required reliability model. It uses the terms whose special meanings have been defined in the foregoing narrative, and it is recommended that the reader survey the notions of phase, function, unit, state, path, and value before proceeding. Further discussions of these quantities will be made following the mathematical discourse, especially in regard to their significance in the procedural application of the model. At this point it is, however, necessary to make certain assumptions concerning the quantities so that the symbology of the analytical formulation may be given a precise interpretation.

Assumptions

1. It is assumed that the unit is the basic element of equipment reliability, so that any probing into its constitution is unnecessary. Its internal characteristics are implicit in the symbol which expresses its reliability as a time-dependent probability function.

2. It is assumed that such probability functions can have quantitative parameters assigned at such time as the model is exercised; for the present only the symbol is needed.

3. It is assumed that the reliability of a unit is the probability that the unit has no internal functional failure over a stated time interval. This probability is derived by means of an analytical density function.

4. It is assumed that all failures in units are of a catastrophic nature, and subsequent recovery (healing) is impossible.

5. It is assumed that a specification of performance and allowable tolerances exists for every unit, and that failure is equivalent to performance outside of this tolerance.

6. It is assumed that within a given phase only one path is meaningful, and that this covers the entire duration of the phase.

Switching between paths during a phase is thus an inadmissible concept. If such a process needs to be considered (as, for example, where redundancy or backup is available) then the complete operation through the phase, incorporating changes as necessary in configuration or processes, is to be identified as a new path.

7. It is assumed that at the beginning of the mission (immediately after injection) there are no failed units.

B. The Figure-of-Merit Model

1. Motivation

Appendix B presents a simple illustration of the distinction between the adopted figure-of-merit model and the conventional classical approach to assessment of system reliability. For the present investigation of Mariner R the character of the mission imposes an unwanted sterility on the classical "go-or-no-go" type of analysis. This is because the mission has the possibility of being sustained, at least in part, in spite of some likely functional failures; that is, there are many paths and consequent routes which have useful results in terms of acquired information and operational experience. It is therefore not surprising to find that the figure-of-merit model is appreciably more complex, both in formulation and use, than the classical model. This complexity is mainly engendered by the multiplicity of routes, but it is clearly worthwhile to pay the price for dealing with many outcomes when the varied objectives of a multipurpose space probe are to be investigated.

It will be seen later that although there are perhaps too many conceivable routes to make a complete analysis tractable, the present approach allows the bulk of them to be neglected, and attention can be confined to "interesting" situations only. Uninteresting, and justifiably neglected routes have the features of low value, in terms of mission objectives, or low probability of occurrence, or both. These are easily excluded at an early stage in the formulated model procedures, as described in the appropriate section of this report.

2. Analytical Structure

Since each phase of the Mariner R mission can roughly be identified with groups of the operational objectives, it is natural initially to adapt the figure-of-merit (FOM) model to a separate reliability and value assessment of each phase. (Later it will be noticed that paths for successive phases are not without interaction: the model acknowledges this fact). The over-all mission reliability is then obtained by combining (with appropriate weighting) the various phase reliabilities.

More explicitly, let V(j) denote an appropriate measure of relative "value" of mission success during the j^{th} phase; then total spacecraft reliability through the first J phases using the FOM concept is defined as

$$\overline{V}(J) = \frac{1}{J} \sum_{j=i}^{J} V(j) \qquad (1 \leq J \leq 4) \qquad (1)$$

In this terminology $\overline{V}(3)$, for example, represents spacecraft reliability figure-of-merit for the first three phases while $\overline{V}(4)$ gives spacecraft reliability for the entire mission.

In view of Equation (1), it suffices to focus attention on evaluating V(j) for each phase. As already noted, there are many paths which the spacecraft can assume during a given phase. Let M_{ij} denote the i^{th} path in the j^{th} phase and $V(M_{ij})$ denote the "value" of spacecraft success accruing when the spacecraft is in M_{ij}. One method of quantitatively determining the value $V(M_{ij})$ requires detailed examination of the mission goals in terms of the importance and desirability of receiving various types of information and experience. This leads to an absolute concept of value dependent on qualities desired of the mission.

Alternatively it is possible to dispense with absolute standards of value and assign a relative value to a path of interest with the normal path value as a denominator. (Formulation is indifferent to the chosen method.)

With $V(M_{ij})$ defined as suggested, let N_j denote the total number of paths in the jth phase. Then the relative "value" of mission success $V(j)$ during the jth phase is defined to be the mathematical expectation of relative "values" of the possible paths during this phase.

$$V(j) = \sum_{i=1}^{N_j} P(M_{ij})\, V(M_{ij}) \qquad (2)$$

where $P(M_{ij})$ is the probability that the spacecraft is in M_{ij} during the jth phase.

The probability $P(M_{ij})$ depends on the routes that could conceivably apply from the first to the end of the (j-1)th phase. Let K_{j-1} denote the total number of possible routes in arriving at this point in time and $r_{k,\,j-1}$ denote[1] the kth route in this set of possible routes; then $P(M_{ij})$ is given by

$$P(M_{ij}) = \sum_{k=1}^{K_{j-i}} P(M_{ij}/r_{k,\,j-1})\, P(r_{k,\,j-1}) \qquad (3)$$

where $P(M_{ij}/r_{k,\,j-1})$ is the conditional probability that the spacecraft completes the jth phase in path M_{ij}, given that the kth route $r_{k,\,j-1}$ was followed through the first j-1 phases; and $P(r_{k,\,j-1})$ is the probability that the kth route is followed.

Note that $P(M_{ij}/r_{k,\,j-1})$ is zero for certain k, due to serial influences among the paths. This eliminates some terms from further computation. In addition, in making calculations based on Equation (3), it is anticipated that the number of summands which must be calculated will be further reduced since many of the products (i.e. individual summands) will be negligibly small. Finally, in view of Equation (2), if an M_{ij} has a $V(M_{ij})$ that is very small, there is no need to calculate the corresponding $P(M_{ij})$.

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[1]The possible routes can be ordered (indexed) in any convenient way, one such being in decreasing order of probability of occurrence.

Each of the route probabilities $P(r_{k,\, j-1})$ appearing in Equation (3) is the probability that the system successfully passes through the sequence of paths that define the route. That is, if the sequence of paths that define $r_{k,\, j-1}$ is denoted as

$$r_{k,j-1} \equiv \left\{ M_{i_1, 1}, \quad M_{i_2, 2}, \quad M_{i_3, 3} \cdots, \quad M_{i_{j-1}, j-1} \right\}$$

where $M_{i_k, q}$ denotes a particular path in the qth phase (preceding the jth phase), then $P(r_{k,j-1})$ is given by

$$P(r_{k,j-1}) = \prod_{q=1}^{j-1} P(M_{i_k, q}) \tag{4}$$

where $P(M_{i_k, q})$ is the probability that the system is in path i_k during the qth phase $(1 \leq q \leq j-1)$.

In review, it is seen that total spacecraft reliability is defined (and may be calculated) using the four basic model equations developed above. Certain refinements of these basic equations are necessary, however, in the event any of the paths M_{ij} can be realized by more than one system state. The remainder of this section is devoted to the development necessary to treat this contingency.

A system state related to a path may be defined in terms of the operability status (up or down) of the various units associated with the path. Some paths demand that a unique set of units be up (i.e., they imply a unique state), while other paths can be realized by more than one set of operable units (i.e., such paths have several states). Each path M_{ij} then can be identified in terms of the collection of states $\left\{S_{ijs}\right\}$, each of which allows the path's existence. If $\mathcal{S}_{ij}$ denotes the collection of states identified with path M_{ij} then, because of the mutual exclusiveness of these states, it is seen that

$$P(M_{ij}/r_{k,j-1}) = \sum_{s} P(S_{ijs}/r_{k,j-1}) \quad , \tag{5}$$

where the summation is taken over $\mathcal{S}_{ij}$. Note that Equation (5) holds when $\mathcal{S}_{ij}$ has only one element (i.e., the path M_{ij} can be effected by only one state); hence Equation (5) is quite general. Combining Equations (3) and (5), it is seen that the "state version" of Equation (3) is

$$P(M_{ij}) = \sum_{s \epsilon \mathcal{S}_{ij}} \sum_{k} P(S_{ijs}/r_{k,j-1}) P(r_{k,j-1}) \quad , \tag{6}$$

where each route $r_{k,\ j-1}$ is now thought[1] of as a sequence of <u>states</u> that could logically follow one another in time and k is summed over all such state sequences. The "state version" of Equation (4) clearly replaces the defining sequence of paths by a sequence of states and, in Equation (4), the $M_{i_k, q}$'s are replaced by the appropriate states and $r_{k,j-1}$ is identified as a <u>state</u> route.

The final level of detail necessary in the development is deriving suitable expressions for the terms $P(S_{ijs}\,/\,r_{k,j-1})$ appearing in Equation (6). Accordingly, for an arbitrarily selected state, S_{ijs}, let X denote the set of "up" units in this state and Y the number of "down" units. For notational simplicity the units in X and Y will be identified, respectively, as

$$\begin{aligned} X &= \left\{ x_1, x_2, \cdots x_u, \cdots x_{n_1} \right\} \\ Y &= \left\{ y_1, y_2, \cdots y_v, \cdots y_{n_2} \right\} \end{aligned} \tag{7}$$

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[1] The symbol $r_{k,j-1}$ is retained in the "state version" since a symbol change appears unnecessary.

where $n_1 + n_2$ represents the total number of units required to define S_{ijs} and it is understood that the x_u's and y_v's are the units required to realize S_{ijs} (i.e., the sth state associated with the ith path in the jth phase). Note that for the normal path, if no unit redundancies exist, the set Y will be empty since no failed units will be allowed, while for other paths, both X and Y will be nonempty.

From the above, it is evident that $P(S_{ijs}/r_{k,j-1})$ is the probability that all x_u's are "up" and all y_v's are "down"; that is,

$$P(S_{ijs}/r_{k,j-1}) = \prod_{u=1}^{n_1} P(x_u) \prod_{v=1}^{n_2} \left[1 - P(y_v)\right] \qquad (8)$$

where P( ) denotes the probability that the unit within the parentheses is "up" during this phase.

Evaluation of the $P(x_u)$ and the $P(y_v)$ is accomplished via classical reliability analysis. Specifically, $P(x_u)$ is seen to be the product of three other probabilities: (1) The probability that unit x_u experiences no failures while it was sitting idly (i.e., on standby) waiting to be turned on to perform its intended task. This probability will be an exponential function (according to the initial assumptions) of what is usually referred to as shelf-life failure rate. (2) The probability that x_u survives the switching action that takes it from standby to operating status. (In other words, this is the probability that activating x_u does not in itself cause x_u to fail.) (3) The probability that x_u once operating successfully operates throughout the time necessary to perform its task. This probability will be an exponential function (by assumption) of the "operating failure rate" of x_u. In symbols, $P(x_u)$ can be expressed as

$$P(x_u) = e^{-\lambda_u' t_1} \cdot p_u \cdot e^{-\lambda_u t_0} \qquad (9)$$

where λ'_u is the standby or shelf-life failure rate of the unit

λ_u is its operating failure rate

t_1 is the duration of its standby time

t_0 is the duration of its operating time, and

p_u is the probability that it can be successfully activated.

It is well to note that for computational as well as modeling convenience, t_1 includes all standby time accruing since the last time the unit was required to operate. Also the time t_0 is the total required operating time in the jth phase and p_u is generally expressed as a function of the number of times that x_u is turned off and on. Finally, if a unit has been continuously operating up to the beginning of the jth phase and is not turned off and on again during the phase, then the first two terms of Equation (9) are unity.

As regards $P(y_v)$, formulas similar to Equation (9) hold. However, the definitions of the time parameters may change, depending on the definition of the degraded state. For example, if the definition of this state precludes the operation of y_v throughout phase j, then the third probability should reflect this by considering survival only up to the initiation of phase j.

This completes the development of the required reliability model for Mariner R. To this point all the necessary concepts have been indicated, symbolized, and then placed in concise algebraic formulas which may be evaluated to yield a variety of numerical estimates. The next section of this report has been written to suggest ways of manipulating in a systematic manner the ideas and quantities constituting the model.

IV. PROCEDURE FOR USE OF THE MODEL

The model which has been developed in this somewhat restricted study of the Mariner R can be most usefully employed for reliability assessment if it is applied in a systematic manner. It is not known at this juncture whether a high-speed computer program would offer profitable advantages in the implementation of a procedure. Clearly, such a program could be designed to assess the consequences of all conceivable paths and routes. There is reason to believe, however, that only a relatively small number of paths have any valid significance in the sense that they offer reasonable probability of success in accomplishing the mission objectives. This could be verified through the introspection gained by a limited amount of added study aimed specifically at making such a determination. The belief that the number of interesting paths is tractably small extends from the observation that there is little equipment redundancy within the system and this, coupled with the serial nature of the mission, attaches near catastrophic results to many imaginable failures.

In the remainder of this section, a discussion of procedures for exercising the model is presented. These represent one way of performing the steps which are involved in a quantitative reliability assessment. Experience in manipulation will undoubtedly suggest modifications to the methods outlined here. At this stage, however, the purpose is to demonstrate the practicability of the model. A worked numerical example included in this report as Appendix C is intended to clarify the procedures relating to the unit-path-route concepts and the ultimate insertion of numbers into the combinatorial expressions of the mathematical model.

A. Unit Selection

Without resolving the question of whether or not to analyze all possible paths, it is evident that a breakdown of the system into reliability units is an essential part of the assessment procedure, for qualitative as well as quantitative purposes. Units have been defined as sets of the system equipment that always operate together to perform some function or portion of a function. A unit may comprise equipment elements that are not part of the same assembly or even of the same "black box;" on the other hand, a given assembly might properly break down into a number of units, each associated with different functions. Selection of units is arbitrary to some degree and is determined largely by the extent to which functions are partitioned and dissected in the analysis.

The number of paths available for analysis is a function of the number of units. If unit selection is too gross, the subsequent assessment will be superficial: some interesting paths will not be included, or certain states within a path will have to be neglected. This difficulty can be avoided by refinement of the units so that a larger number are specified. If the breakdown of individual functions is carried too far, however, it causes analysis of very many paths when distinctions between them are not especially significant. Any over-all selection of system units will represent some compromise between these limiting situations.

The selection adopted for this study comprises 58 units. Some refinement of a few of these units will be necessary in any actual exercise of the model because some essential details of redundancy and certain switching operations have not been brought out. Such a refinement will require reference to wiring diagrams and to other design documents which were not readily available during this study.

The selection list has been divided according to the major functions previously defined, and wherever possible the appropriate component code designations have been taken from Specification MR-4-120D of the Mariner R SDS. Because the component code does not, in general, agree with the unit selection list, a separate numbering scheme has been assigned to each unit. The first digit identifies the major function served by the unit. The next two digits are used merely for serial identification and have been assigned arbitrarily but in ascending sequence to the units within a function. The functional identifications are listed:

100	Measure Science
200	Measure Engineering and Encode Data
300	Command
400	Control and Sequence
500	Supply Power
600	Control Attitude
700	Guide
800	Telemeter

The system diagrams for the implementation of the above-listed functions[1] show the manner in which the unit selection has been made, and give the unit identification numbers. The units are tabulated below by major function with the applicable component codes shown.

1. Measure Science Units

These units do not include the transducers and instruments which actually make scientific measurements. The selection is concerned solely with equipment which switches the units and conditions the data.

Unit	Code	Description
101	20A1	Science power switching unit
102	20A21 through 20A24	Science data conditioning system
103	20A25	Science transformer rectifier

2. Measure Engineering and Data Encoding Units

Because of the close relationship between the engineering measurement functions and the encoding of data, these unit selections include the components of the data encoder. Availability of design information on this segment of the spacecraft system permitted a somewhat finer unit breakdown than was used for the other functions. In some

[1] Refer to Section II of this report.

cases, however, this design information did not include component code designations and the code is not tabulated for these units.

Unit	Code	Description
201	6A1	Subcarrier generators, modulators, and mixer
202	6MT2	P/N generator
203	--	Science-engineering transfer switch
204	--	OR gate for digital and analog data
205	6MT1	A-D converter
206	6MT3	Transfer register
207	6MT4	Event registers and sequencer
208	6MT2	Master counter
209	6K1	Deck A, high rate
210	6K1	Deck B, high rate
211	--	Science word counter and switch control
212	--	Measurement transducers for deck B
213	--	Measurement transducers for deck A
214	6K1	Deck C, medium rate
215	6A1	Low-level amplifier
216	--	Measurement transducers for deck C
217	--	Programmer for low-rate decks
218	6K2	Deck F and associated transducers
219	6K2	Deck E and associated transducers
220	6K1	Deck D and associated transducers
221	6TR1	Transformer rectifier for encoder
222	--	Blip transducers

3. Command Units

These units as a group provide for subcarrier demodulation, decoding, and execution (by relays) of the various commands transmitted from the DSIF. The antenna is included but the r-f reception and demodulation are grouped with the telemetry function and are not listed here.

Unit	Code	Description
301	3A4	Command processing, storage, and switching
302	3A1	Data subcarrier demodulator
303	3A2	Synchronization subcarrier demodulator
304	3A3	Transformer rectifier for command system
305	2A13-14 2W1-2-3	Command antenna and feeds

4. Control and Sequence Units

The CC and S comprise most of these units, although some of the redundant command relays have been included. This function offers the greatest opportunity for additional refinement of the unit selection, given the necessary design detail. Some of these units are involved in the performance of groups of functions which might be separated under some circumstances if the resulting impairment gave rise to an interesting path.

Unit	Code	Description
401	5A1-2	Central clock and launch counter
402	5A6-7	Stored command register and decoder
403	5A4-5	Maneuver clock and duration counter
404	5A3	End counter
405	5A8	Transformer rectifier and override relays

5. Supply Power Units

Both a-c and d-c supplies are covered in this tabulation. Transformer/rectifier units assigned specifically to other functions are not included here.

Unit	Code	Description
501	4A11-12 4A15	Solar cell panels, latches, and pyrotechnics
502	4A1	Power switching logic and oscillator
503	4A4	Regulator for d-c supplies
504	4A7	Battery charger

Unit	Code	Description
505	4A14	Battery
506	4A8	Power amplifier, 400 cps
507	4A9	Power amplifier, 2,400 cps
508	4A6	a-c oscillators and synchronizer

6. Control Attitude Units

These units are involved with the coasting-attitude control although some of them are allied to other functions. In particular, the antenna hinge is included here rather than with the telemetry function because its role in the latter application is somewhat less vital.

Unit	Code	Description
601	7A1-2	Gyros and electronics
602	7A18, 7A33 through 7A36	Valves and jets, cold gas tankage, and switching amplifiers
603	7A11, 7A13	Hinge, actuator, and servo
604	7A10	Earth sensor
605	7A25 through 7A31	Sun sensors
606	7A18	Control and logic

7. Guide Function

Because of the one-shot nature of this function most of the equipment peculiar to the midcourse maneuver is highly interdependent and can be lumped into a single unit. Those units within the coasting attitude control function specifically used for the guide function are relisted.

Unit	Code	Description
701	7A2	Gyro capacitors for position mode
702	7A4, 7A5a, 7A6a, 7A7a, 7A8a	Rocket motor, propellant tankage, valves, accelerometer, autopilot, and jet vanes

Unit	Code	Description
601	7A1-2	Gyros and electronics
602	7A18 7A33 through 7A36	Valves and jets, cold gas tankage, and switching amplifiers
603	7A11 7A13	Hinge, actuator, and servo
606	7A18	Control and logic

8. Telemeter Function

A number of the units listed under the engineering measurements and the command functions might also be looked upon as serving the telemeter function. This is not a case of dual-purpose use but rather a matter of defining the scope of the function. As here defined, the telemeter function is limited principally to the operation of the transponder in both the phase coherent and incoherent modes.

Unit	Code	Description
801	2A11-12 2A3-4-5	Directional antenna and r-f amplifier
802	2A10 2A3 2W6	Omni-antenna and r-f amplifier
803	--	Antenna transfer switch
804	--	Oscillator transfer switch, modulator, and multiplier, r-f driver
805	--	Crystal oscillator
806	2A4	Transformer/rectifier for transponder
807	2A1-2	Voltage controlled oscillator, AGC loop, VCO loop, receiver front end and i-f strips, subcarrier separator

9. Units for Other Components and Systems

The eight functions just enumerated and used for the identification of reliability units of groups of equipment do not explicitly include certain of the onboard quantities. The structure and the wiring harnesses are in this category, as are pipes, mechanical and electrical connectors, latches, squibs and surface finishes. In this preliminary assessment of the spacecraft reliability, it is not intended to assess these things as separate entities, but rather to take note of their occurrences in support of the defined functions as special units, or "support units," where this is appropriate, or to take their contributions to system reliability as included in the existing specified units. For example, the wiring harness and connectors functionally can be considered as a part of the T/R unit, and the reliability of these components will then appear as part of the reliability assigned to the T/R unit proper.

It is not convenient to deal with the structure in this way (as part of other units on a piece-by-piece assignment.) Experience in other reliability assessments (especially that for OGO)[1] has shown that spacecraft structures are the strongest single component in equipment reliability, and the expected failure rates are such as to make detailed analyses superfluous until such time as electronic and electromechanical devices are much improved over their present life expectancies. There is only one moving part in the Mariner structure (the antenna hinge) which is within the scope of this investigation, and this logically is a part of the optical earth sensor reliability unit. The structure in question is thus entirely a static one, adequate to withstand the loads imposed by launch. Loads expected during the mission proper are in comparison negligible assuming no runaway in the attitude and propulsion systems. In this event, structural failures are regarded as induced effects, and the prime causes are the actual failures.

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[1] "Preliminary Reliability Assessment for the Orbiting Geophysical Observatories" PRC R-243. February 1, 1962.

B. The Normal Mission and Necessary Units

The complete success of the Mariner R mission can be achieved only if all of the units enumerated in the previous section operate in the correct manner when called upon. This statement would not be valid if duplicate equipments or redundant units existed within the system, but the lack of such redundancy is a salient characteristic of the spacecraft. It is true that a limited degree of operational redundancy is provided through the medium of commands transmitted from the DSIF; however, the use of these commands has been programmed into the flight sequence in most instances, and it is not illogical to consider each command execution as a backup objective of the mission. From this viewpoint, therefore, the normal mission could be defined as one throughout which all units operate as scheduled.

1. Normal Paths

The mission is divided into four phases as previously defined, and this permits a slightly different approach to the definition of a normal mission. The possibility of a deviation arises because the progression from phase to phase is accompanied by the dropping of the requirements for certain units. An obvious example is the set of units directly concerned with the midcourse maneuver. Once the maneuver has been executed, or attempted, there is no need for these units, and their condition in terms of being operable (up) or nonoperable (down) is of no consequence in phases III and IV.

Another effect of the breakdown of the mission into phases is the absence of a requirement for certain units during a phase, but the subsequent need for these units in later phases. It is worthwhile to take note of those units which are temporarily not required but for which a need will subsequently be developed.

From foregoing considerations, therefore, a normal mission is defined as a succession of four phases, each of which is completed with all required or subsequently required units in the up condition. In terms of the formalized concepts which have been established for the model, a normal mission is that route which consists of the connection of the four normal paths. A normal path, in turn, is the path which traverses a phase with all required and subsequently required units in the up condition. A meaningful description of the normal mission, and, hence, of the normal path for each phase is the tabulation of the units not required for a given phase or for the phases which follow. This tabulation is given in Exhibits 16, 17, 18, and 19. As a matter of information, the tabulation also lists the units which are not required for a given phase but which are subsequently required for a normal mission. These exhibits reveal that a truly normal mission demands that all units be up during phases I and II, that the omni-antenna and midcourse maneuver units are no longer required after phase II, and that the engineering measurements are not required after phase III.

2. The "Not Required" Category

The attempt to specify the normal mission in terms of unit condition has allowed the introduction of a "not required" (N/R) condition, or category, into which units may be placed. This category is in addition to the up and down categories previously defined. Some reflection on the meaning of the N/R category indicates that it is actually a combination of both the up and down conditions. For an illustration, consider the trivial case of a system composed of two units, A and B. Assume that a phase is reached where B is no longer required but A must be up to attain the performance objectives of the system. It is evident that either of two system states will satisfy the specified conditions for the phase, namely A up and B up, or A up and B down. These are mutually exclusive states, and the probability of achieving either of them will include both the probability that B is up and the probability that B is down. This total probability is unity and the same result could have been arrived at by ignoring the condition of B and eliminating it from any computation of state probability. This is what is meant by the N/R category, which will be shown to have useful applications in the analysis of system reliability.

It must be emphasized that the N/R category should be used only for units no longer required after some phase of the normal mission.

EXHIBIT 16 - UNITS NOT REQUIRED FOR NORMAL PATH - PHASE I

Unit	Description	Subsequently Required in Phases
101	Science power switching unit	III - IV
102	Science data conditioning system	III - IV
103	Science transformer/rectifier	III - IV
211	Science word counter	III - IV
402	Stored command register and decoder	II
403	Maneuver clock and duration counter	II
701	Gyro capacitors for position mode	II
702	Rocket motor, propellant tankage valves, accelerometer, autopilot, and vanes	II
801	Directional antenna and r-f amplifier	III - IV

EXHIBIT 17 - UNITS NOT REQUIRED FOR NORMAL PATH - PHASE II

Unit	Description	Subsequently Required in Phases
101	Science power switching unit	III - IV
102	Science data conditioning system	III - IV
103	Science transformer/rectifier	III - IV
211	Science word counter	III - IV
603	Hinge, actuator, and servo	III - IV
604	Earth sensor	III - IV
605	Sun sensors	III - IV
801	Directional antenna and r-f amplifier	III - IV

EXHIBIT 18 - UNITS NOT REQUIRED FOR NORMAL PATH - PHASE III

Unit	Description	Subsequently Required in Phases
301	Command processing, storage, and switching	IV
302	Data subcarrier demodulator	IV
303	Synchronization subcarrier demodulator	IV
304	Command transformer/rectifier	IV
402	Stored command register and decoder	IV
403	Maneuver clock and duration counter	None
701	Gyro capacitors for position mode	None
702	Rocket motor, propellant tankage, valves, accelerometer, and autopilot	None
802	Omni-antenna and r-f amplifier	None

EXHIBIT 19 - UNITS NOT REQUIRED FOR NORMAL PATH - PHASE IV

Unit	Description	Subsequently Required in Phases
204	OR gate for digital and analog data	No Subsequent Phases
206	Transfer register	
207	Event registers and sequencer	
208	Master counter	
209	Deck A - high rate	
210	Deck B - high rate	
212	Measurement transducers for deck B	
213	Measurement transducers for deck A	
214	Deck C - medium rate	
215	Low-level amplifier	
216	Measurement transducers for deck C	
217	Programmer for low rate decks	
218	Deck F and associated transducers	
219	Deck E and associated transducers	
220	Deck D and associated transducers	
222	Blip transducers	
402	Stored command register and decoder	
403	Maneuver clock and duration counter	
701	Gyro capacitors for position mode	
702	Rocket motor, propellant tankage, valves, accelerometer, autopilot, and vanes	
802	Omni-antenna and r-f amplifier	

This restriction is a consequence of the inability to consider the movement of units from the down category back to the up category. If a unit is not required in a given phase, placing it in the N/R category voids the opportunity of ever returning it to the up category. Should that unit be required in a subsequent phase it must be treated as though it were required in all prior phases if the normal route is to be followed.

C. Degraded Paths and Figure-of-Merit

Up to this point, the procedural steps have included the selection of a set of units and the specification of a normal mission in terms of unit condition. It was noted that the normal mission would be achieved only if all required units remained up throughout the mission. If the normal mission were adjudged to be the only valuable route which could be followed by the spacecraft, a classical approach could be adopted for the reliability assessment. The reliability model would consist of a string of units required for each phase and the reliability would be the joint product of the individual unit reliabilities over each phase.

1. Degraded Paths

While the ultimate objective of the Mariner R spacecraft may be regarded as the telemetering of scientific measurements from the vicinity of Venus, it must be recognized that there are many corollary objectives, as indicated in the qualitative assessment contained in this report. It is evident that, whereas only one path for each phase will attain all of the objectives of that phase, partial fulfillment of objectives can be achieved in a variety of ways. Each such way is a degraded path, and the degradation is brought about by the failure of the system to perform some of the functions required for that phase. A degraded path, therefore, is characterized by two related features:

a. It involves the failure of certain required functions either during the phase covered by the path or in a prior phase and continuing through the given phase.

b. It has a lesser value than the normal path through inability to accomplish all the desired objectives of the phase.

The first feature serves to distinguish between paths, and is useful as a means of initially specifying a path. The second feature provides a method of applying the figure-of-merit reliability assessment to the mission. It is this point which will be discussed next.

2. Figure-of-Merit

The concept of applying a quantitative measure of value to a degraded path follows naturally from the consideration of the extent to which the path achieves the objectives of the phase. If a relative value measure is adopted, the normal path is conveniently used as a datum, and a nondimensional value of unity is assigned to this path. All other paths, being degraded, can be associated with a relative value rating of less than unity. The limiting value rating of zero is assigned to any path that contributes nothing toward the achievement of the phase objectives. A path which leads to a partial fulfillment of phase objectives is accorded a relative fractional value rating of a magnitude that reflects the extent to which it approaches the normal path in terms of accomplishment of objectives. In order to develop an absolute measure of value for the figure-of-merit reliability it must be noted that some objectives are more desirable than others. The measurement of desirability is a matter of human judgment tempered by sound engineering principles. Once this judgment is formed and the objectives are weighed and ranked, the task of assigning value ratings to paths can be made reasonably straightforwardly. In any event, the model as formulated is not attached to any specific method of determining values, either relative or absolute.

The use of the value concept in arriving at a figure-of-merit reliability assessment is explained in the Mathematical Formulation (Section III) and exemplified in Appendix B. The principal task in the assessment, therefore, is the computation of the reliability of each of the various paths, rather than the assignment of a value rating to each path. Quantitative assignment of value ratings is not within the scope of this study, and no further attention will be directed toward this aspect of the reliability assessment.

3. Path Listings

To realize maximum advantage from the figure-of-merit reliability approach it is incumbent upon the assessment team to include all significant elements of expected value for each phase. In general, a value element will be significant if both the value rating and the reliability of the corresponding path are significant. Since the element comprises the product of these two figures, it will not be any more significant than the least significant of either of them. A value element worthy of inclusion in the assessment arises from a path which has a nonnegligible probability of completion and over which a reasonable proportion of the scheduled objectives are fulfilled.

The task of listing the significant paths is not a fully closed operation in the sense that a predetermined number of operations will assure that all such paths have been included. The application of engineering judgment coupled with a thorough knowledge of the system, the flight sequence, and the objectives, enables these operations to be compartmented in a number of ways. Initially, it would be well to examine the objectives of each phase in turn. Confining attention to a single phase, the major functions should be considered one by one. A list of likely or significant impairments of each of these functions can be compiled for ready reference and used repeatedly. The consequences of each functional impairment throughout the particular phase under examination can be deduced from familiarity with the system and the mission. If the consequences are catastrophic, in that essentially no important objectives can be achieved, the path will undoubtedly be marked by a near-zero value rating, and consideration of it can be dropped. Alternatively, if a particular set of objectives obtains only through a highly improbable combination of simultaneous functional failures, the expectation for the occurrence of such a path will be negligibly small and this is reason for discarding it.

4. Path Specification

The compilation of a path listing can be stopped at any convenient point, and resumed at any time, prior to the summation of value elements to obtain the expected value. Assuming that an initial path listing has been assembled, it next remains to specify the exact functional and operational configuration peculiar to each path. The term "exact" is used here as applicable to major functions or suitably broad portions of functions. This is important because it is not intended that path specification shall degenerate into a matter of merely listing unit states. The assessment philosophy is founded on the assumption that, in general, many equipment states will produce an equivalent functional impairment and hence equivalent loss of objectives. If the functional configuration is specified to begin with, the task of ascertaining the corresponding set of equipment states will be a deterministic procedure, readily handled by systematic and orderly steps. It is essential, however, that the path specification be definitive so that there is no ambiguity relative to the condition of the principal functions. Unlikely failure combinations can be avoided if the path specification is kept sufficiently simple so that the resulting situation is easy to imagine in its totality regardless of the number of states which might produce it.

D. Path Reliability

Path reliability is defined as the probability of successfully traversing a phase via a specific path. In general, a multiplicity of unit states will lead through any given path. Each unique state will have associated with it a calculable probability of occurrence and will contribute to the path reliability. Path reliability is, therefore, the sum of the probabilities of the various states which lead through the path.

1. State Identification

From the path specification it is in principle possible to list all of the units which could potentially produce the specified functional failure. For a complex failure situation it may be necessary to list sets of units which must be down in combination to effect the stated failures. Even for single functional failures where a string of units could cause the impairment, consideration must be given to the possibility that the units in the string will fail not only singly but in all possible combinations. Each combination may have a nonnegligible probability and will contribute to the over-all path reliability.

When the down units associated with a path have been listed, it is necessary to search out the units which are not required. This listing will include units which are not required because they are no longer needed (as with certain units in the normal state) or it may contain units which are not required because they can no longer serve any useful function under the specified path failure conditions. This will be discussed in more detail in the subsection on unit dependency. Units which are truly not required can be listed in the N/R category and their reliabilities can be ignored.

The units which have not been listed as potentially down or not required must necessarily be up for the states being analyzed. It will usually not be required to list the up units. Most path specifications represent a deviation from the normal path and the majority of the units will be up as in the normal path.

The states leading through a given path will be fully identified by the listing of all system units in the three unit categories. It remains to ascertain that the states are unique, i.e., mutually exclusive. If the N/R category were not used, all states except identical states would be mutually exclusive. When the N/R category is employed, both the up and down states of the units so listed are included in the corresponding state probability. Accordingly, any other state which differs only to the extent that some of the N/R units have been relisted in the up or down categories will merely duplicate a portion of the first state. This condition can usually be avoided by carefully noting which units are listed as N/R in a given state and being certain that there are no other states which differ from the first only by the shifting of units into and out of the N/R category. Any two states are uniquely different only if there is some interchange between the up and down listings regardless of the composition of the N/R categories. If there is any doubt concerning the exclusiveness of two states, it can be resolved by examining the down lists for the two states and noting the differences. If these differences can be accounted for by shifts into and out of the N/R lists, the states are not mutually exclusive.

2. Route Formulation

The concept of a route as a connection between states in adjoining phases is illustrated in Exhibit 20. A route is here shown as the interconnection of paths; however, if a path comprises various states, then it is generally true that several routes can be associated with any path.

It is necessary to introduce the idea of routes because allowance must be made for the failure of specified down units in phases prior to the phase of the path being analyzed. If a functional impairment implies that a unit is down throughout a phase, that unit will be down with probability one if it has failed in any prior phase. It can be seen immediately that there is a possibility of at least two states for each prior phase that will qualify in bringing about the specified failure, viz, the unit could fail in the prior phase and remain down throughout succeeding phases, or the unit could remain up during the prior phase and fail during a later phase. Each of these occurrences has associated with it a probability, and it is necessary to include all such probabilities in the computation of the path reliability. In practice, the number of possible routes is sharply limited by the restriction that failures are permanent. It will generally be true that no route will serve as a valid entry to a given path if that route includes unit failures which are not included in the path specification. The matter of routes, then, must be investigated once the states within a path have been identified, and all possible routes which could lead through that path must be delineated.

E. Unit Dependency and Redundancy

Path reliability can be computed from the assembly of unit strings which make up the various routes leading through a path and the multiple-state possibilities within a path. To effect the computation, it is requisite that the reliability of each of the units be known. This reliability is a function of the history of the unit from the beginning of the flight and will, in most cases, be a composite of the reliabilities of the component parts which are included within the unit. This matter has been considered in somewhat more detail in the Mathematical Development.

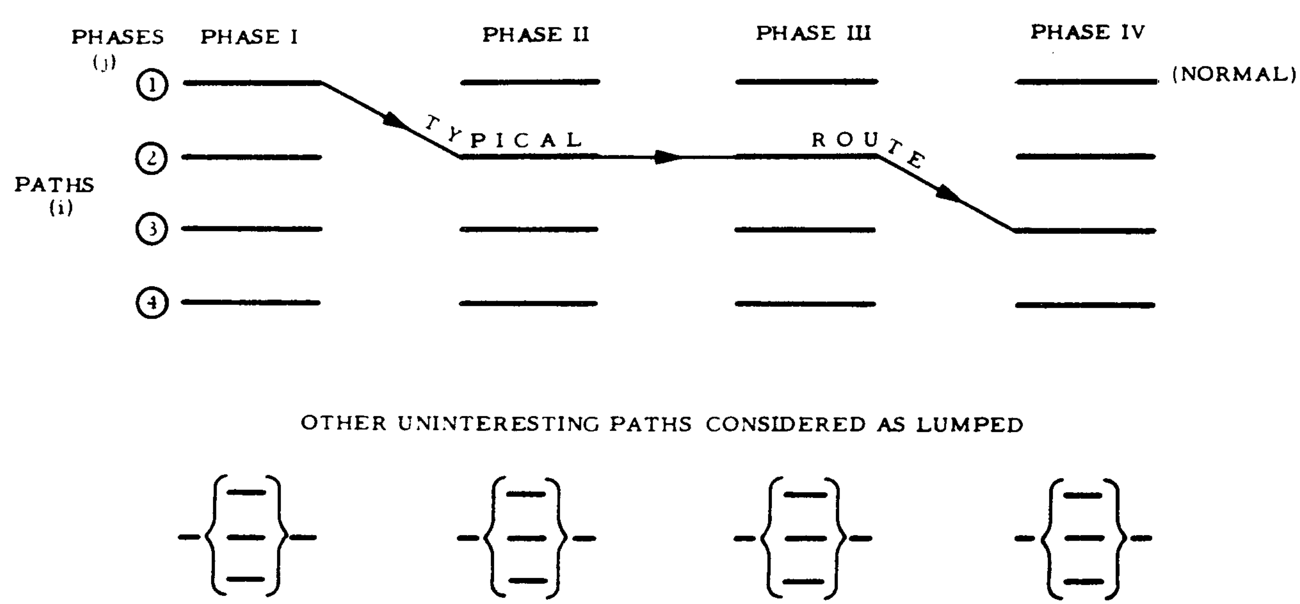

EXHIBIT 20 - PATHS, ROUTES, AND PHASES

1. Unit Dependency

It was noted previously that under some conditions a unit or group of units could be categorized as not required under the stipulation that another unit had failed. The justification for this lies in the fact that some units depend on others to perform any useful function. This can be illustrated by an example taken from the data encoder and depicted in Exhibit 21. This simplified block diagram shows that all engineering data must funnel through an "OR" gate which has been assigned unit number 204. It is evident that a failure of this unit will preclude the transmission of any engineering measurements. Under these circumstances the functional value of most of the units required for engineering measurements will be negated. Units 205 and 206, for example, serve no useful purpose if unit 204 has failed. The same is true for the many units which compose the commutator and the blip-event registers. In enumerating the states which include a failure of unit 204, it is essential to eliminate all units which depend upon it, since the same functional degradation applies whether or not these units are up or down.

To assure that all such cases of unit dependency are taken into account, it is suggested that a dependency list be compiled. Such a list could be readily assembled by considering each unit in turn, and, through reference to the system diagrams, noting all other units which are wholly dependent upon it for producing any useful output. This is a one-shot task in that, once accomplished, it will serve in the analysis of all paths and states. One byproduct of such an effort would be the uncovering of complete interdependencies. If two units are completely interdependent, then they have been incorrectly selected and should be combined into a single unit.

2. Redundancy

To the level of detail covered in this study, little equipment redundancy has been identified in the spacecraft system. The command function is utilized for backup purposes in assuring the proper sequencing of certain selected events. In this role it provides a degree of operational

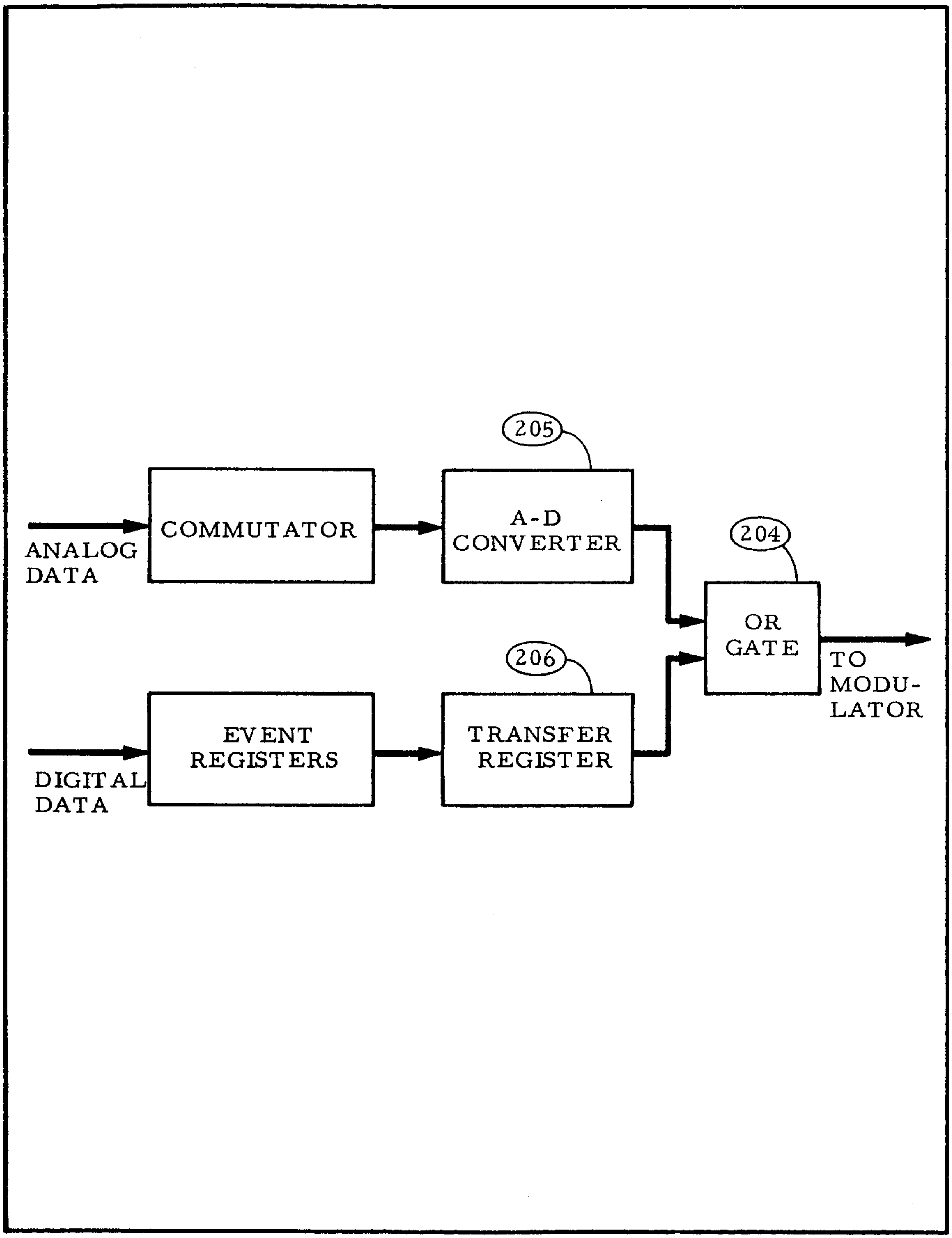

EXHIBIT 21 - SEGMENT OF DATA ENCODER

redundancy; however, it is not to be considered as an equivalent alternate because it functions through a significantly complex chain of units. This is portrayed in Exhibit 22, which indicates that the command loop is closed through five units, each of which undoubtedly possesses a finite probability of failure.

It will be necessary to examine the system design documents in greater detail to show the correct location of the command loop in its redundant role. The current unit breakdown is not sufficiently refined to avoid showing the command loop around units for which it is not truly redundant. Many of the units provide multiple functions which are distinct even though closely related. If the command backs up only one of these functions, then the unit must be partitioned to permit the introduction of the command loop.

3. Failure Modes

The establishment of unit reliability is usually predicated on the assumption that a unit failure is catastrophic; i. e., the unit can be considered only as fully operable or completely inoperable. Partial system failures can be handled at the functional level, and the path philosophy was designed to provide this sort of flexibility. Efforts to carry this approach down to the unit level would quickly render the assessment unmanageable and would obscure the pertinent results. For a few selected units the consequences of different modes of failure may be important enough to warrant devising a method of handling them. An example of this is unit 803, the filament switch which transfers the spacecraft transmitting function between the omni and the directional antennas. It is highly probable that a switch will fail in one position, in which case it has failed as a transfer means, but not as a gate for one of the outputs. This is an example of distinct failure modes which could be introduced into the analysis by partitioning of the unit. The use of two units in the place of the single unit 803 would clearly increase the number of state possibilities from two to four. Depending upon the depth to which the assessment is to be carried, the partitioning of units can be an effective means of permitting various modes of failure to be considered.

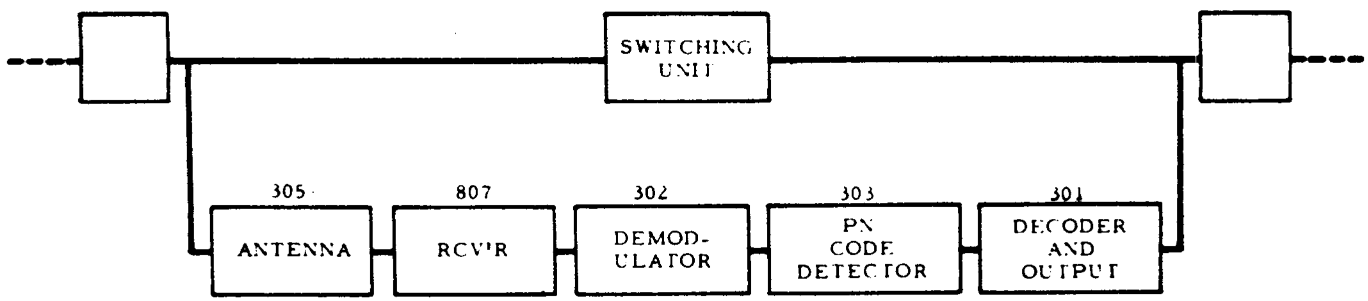

EXHIBIT 22 - COMMAND REDUNDANCY LOOP

F. Summary of Procedure

It was stated at the outset that the procedure for implementing this reliability assessment might well take the form of a high-speed computer program, or it might consist of an orderly set of operations with the results being obtained through manual calculations. The two approaches would differ in some respects; however, the basic framework which has been established by this study can readily serve as the guide for either method. The mathematical model is tailored to the Mariner R system and mission but is sufficiently general to allow latitude in the details of the assessment procedure. Regardless of the approach to be adopted, the procedure will be characterized by certain salient steps which have been covered in the foregoing discussion. It is appropriate to summarize the more important steps as follows:

1. Group all of the components in the total system into units, and identify the units by number to facilitate later reference to them.

2. Considering each individual phase of the mission, note the relation between each of the major functions and the objectives of that phase.

3. Form a judgment of the consequences of the loss of a function. If a significant proportion of the objectives can be achieved despite the functional loss, the imagined situation qualifies as an interesting path for traversal of the phase.

4. Proceed in this fashion and include partial functional impairment and combinations of functional failures until all paths of interest have been identified.

5. From the system diagrams and other pertinent equipment descriptions make a list of the units and unit combinations which could cause the functional impairment characteristic of each path. Conversely, note all remaining units that are required for the unimpaired functions of that path. This identifies the states for a path.

6. With each path it will generally be possible to associate a number of paths in prior phases that could logically lead to the path being analyzed. Each possible serial connection of prior paths with the path being analyzed is a route.

7. Knowledge of the reliability of each unit can be gained from a study of the failure rates of equipment composing the unit, and from the prior history of the unit. From these unit reliabilities the various state probabilities can be computed.

8. Each state probability, conditioned by the probability of the route which led to it, contributes to the probability of the path. Path probability is the sum of all such contributions.

The procedure is not complete at this point for it remains to integrate the various path probabilities into a figure-of-merit assessment; however, the steps described above will attach quantitative probability estimates to all of the paths considered to be significant. A review of these will disclose if any of the paths selected for analysis have negligible probability of attainment, in which event they can be discarded. At the same time, an estimate can be made of the total probability of discarded paths, or paths not considered, and this will indicate the extent to which the selection covers the range of all possible paths. This circumspect look at the path selection will serve to reveal gross omissions or other errors of large magnitude in the analysis.

The assignment of a value rating or function to each path is based on the extent to which the path fulfills the objectives of the phase and an estimate of the relative worth of the objectives. This must be accomplished for each path; the resultant path value rating multiplied by the path probability will produce an element of the expected value for that phase. The figure-of-merit is arrived at by appropriately averaging the expected values of the phases.

V. QUALITATIVE ASSESSMENT OF SUCCESS EXPECTED IN MISSION OBJECTIVES

A. An Assessment

1. The Specific Mission Objectives

The JPL work statement for this investigation indicates a particular interest in the probability of success expected qualitatively for the following objectives:

a. Communication with the spacecraft from the vicinity of Venus

b. Scientific data from the vicinity of Venus

c. Communication with the spacecraft from interplanetary space

d. Scientific data from interplanetary space

e. Data on the operation of the subsystems in the interplanetary environment

f. Data on the causes and modes of failures in the spacecraft.

A brief contemplation of these objectives to be appraised reveals that they are almost incapable of being considered independently. For this reason, the remarks which follow deal with the topics in what is considered to be a more tractable sequence. The basic qualities essential to the attainment of any value from the mission are discussed first; subsequently the more ambitious objectives are able to be rationalized.

The starting point for the mission as far as the present analysis is concerned is immediately following injection (which event is assumed to occur so that the planned mission is possible). Due to the fact that certain of the spacecraft systems are required to operate through injection, it may be assumed further that the power supply (on battery), the clock in the central computer and sequencer, the data encoder and the telemetry transmitter and transponder are all in proven up condition. Whether the transponder is on coherent phase lock or on its internal crystal radiofrequency reference is not known at the time of writing; this fact, however, is not of significance[1] at this point in the mission. From these initial assumptions it is now possible to proceed qualitatively as follows. The objectives are most conveniently considered in the reverse order to that listed above, due to the sequence in which events of the mission inevitably occur.

2. Overriding Importance of Communications

Once the Mariner R has separated from the booster, all evidence concerning its performance can only be obtained by virtue of the radio communications channel. Thus any qualitative appraisal of the degree of success expected for the various mission objectives is, from the reliability-block viewpoint, in series with the vehicle communications system. This requires that all objectives must be lower in probability of attainment than the reception of communications at the DSIF.

As time elapses over the mission, the chance for failures to occur and degrade the communications equipments must increase. Moreover, the effects of potentially disturbing events such as the maneuver can only lead to an increase in the probability of communications failure. While these time-dependent matters are vying for the possibilities of adverse consequences, the range over which communications is required is steadily lengthening, so that any tendencies towards marginality in performance due to signal strengths are becoming more and more significant. A step in this range-dependent effect of considerable magnitude occurs especially when the path loss is such that the omni-antenna is of insufficient gain. Then only the directional system is usable so that the redundancy afforded by the duplex antennas and power amplifiers is lost.

These matters are illustrated in Exhibit 23, which shows in addition the qualitative expectations for the other specific mission objectives. These expectations are discussed in the following paragraphs.

3. Data on Failures

Since the telemetry and data encoder are working at the moment of injection, there is a highly significant probability that the first

[1]Except as it affects reception of commands. These are not normally called for at this time.

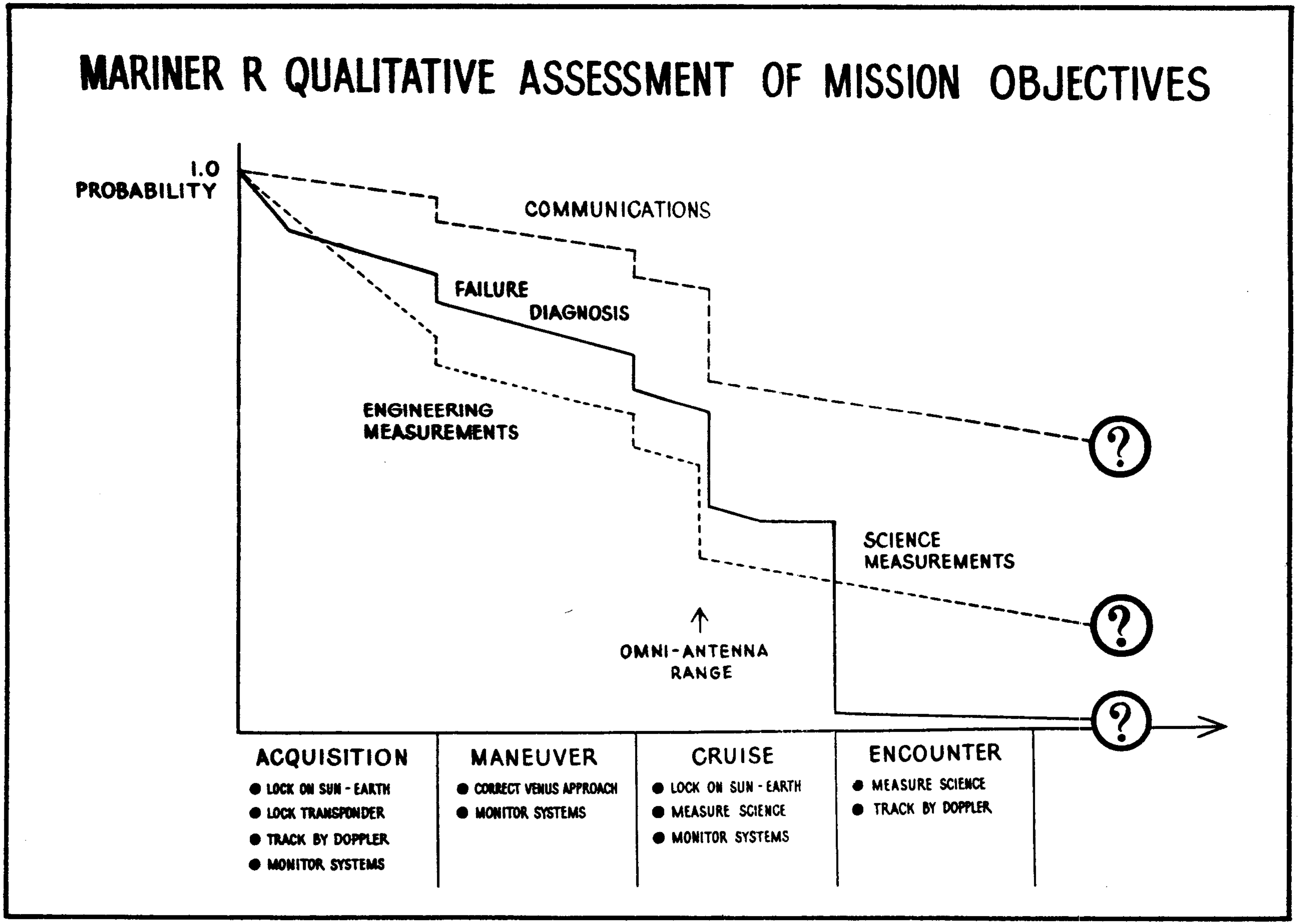

EXHIBIT 23 - MARINER R QUALITATIVE ASSESSMENT OF MISSION OBJECTIVES

few data frames of engineering measurements will be received (at the launch facility, if such is equipped for reception) after the potentially upsetting event of separation. Subsequently the readout of the CC and S events counter will show if the solar panels unlatched and the attitude control system came on, as planned. If these events do not occur, it is reasonable to expect that the telemetry will indicate the failure to function, as the elapsed time for injection is sufficiently brief that failures in telemetry equipment known to have been working at injection are quite improbable.

As concerns the question of obtaining data on failures in the telemetry itself, the probability of success seems high. Garbled data from the telemetry concerning the engineering measurements, suggesting failure somewhere in the data encoder, should enable some subsequent rational evaluation of the type of malfunction to be conducted. (Complete loss of signals from the spacecraft without prior indication of any impending malfunction is the most unwelcome accident that has to be anticipated. This will of course render the rest of the entire mission valueless, and diagnosis of the fundamental cause will be only speculative.)

Taking the more optimistic view, let it now be assumed that the data from the telemetry is successfully received and interpreted according to specifications. Operational failure of the power supply battery charger is immediately recognizable, and may be checked against the status of solar acquisition. On a somewhat more extended time scale, the performance of the temperature control arrangements will become apparent; this will provide further evidence concerning the vehicle orientation. Substantially independent from the telemetry of engineering data proper is the status of the phase-lock system for the transponder. The doppler measurements which are essential for vehicle tracking will indicate if this is performing as intended.

From the above comments it is to be concluded that for the period prior to the commencement of earth acquisition there are good expectations for monitoring performance and diagnosing failures in all the systems performing at this time. It is important that the monitoring of the performance of certain events which have a command backup or override capability be successfully accomplished (otherwise the need for a correcting command will not be evident when it should be). In this regard it is therefore pertinent to notice that the interpretation of the received telemetry data be as rapid as can be realized, not only for the planned injection trajectory, but also for trajectories which might occur due to injection errors. Recall that so long as escape energy is realized, the opportunity for interplanetary measurements exists.

The onset of earth acquisition is the next event where malfunctions may be met with. For the several days prior to this event, the operation of the vehicle has been in a quasi-cruise condition, with sufficient opportunity for telemetry and its interpretation that the quality of the mission to this time may almost certainly be closely followed. Earth sensing involves prior success in solar acquisition, and, of greater interest, the satisfactory functioning of the hinge position program and servo, as well as roll attitude control. There is a close dependence between these separate functions, so that the diagnosis of faults in the event of trouble in earth acquisition is not as direct as for things which have been of interest prior to this time. With all engineering measurements available, distinct observations of sensors, roll errors and hinge angle will enable most conceivable faults to be elucidated. Without such measurements, but with successful telemetry carrier reception via the directional antenna, and with use of the roll and hinge override commands, useful deductions are still practicable. This combination affords a redundant capability for fault identification in the earth acquisition system, so that the probability of success in the objective in question is high.

Considering now the maneuver, the first significant event is the receipt at the spacecraft of the stored commands. Such reception is an event monitored by the telemetry, and there is no alternative means for determining if they have been correctly processed. Moreover, the condition of the command data sync channel is needed to be known (also by the telemetry) before the commands can be sent with any assurance that they will be accepted as intended. Subsequent events of the maneuver are the receipt of the initiate signal, followed by the firing of the pyrotechnics in the motor. These are counted by the data encoder and put into the telemetry, but the actual magnitude of the maneuver effects is not capable of being known until tracking information is accumulated following the impulse. Failure to perform the desired maneuver is therefore not easy to interpret as to cause, even with the full capability of the engineering measurements. Without them, it is unlikely that the maneuver would be attempted.[1]

Monitoring the reacquisition of the sun-earth references by the attitude sensors can be done in a manner similar to the previous acquisition events. In particular, earth acquisition is readily recognized by several indications, including the switchover to the directional antenna and the onset of the cruise telemetry mode which includes the science data. Antenna switching and aborted acquisitions may be explored additionally by means of the backup and override commands. There is thus a redundancy in faultfinding opportunities at this juncture.

In the cruise phase recognition of failure modes becomes increasingly less urgent since little can be done to circumvent any untoward event. Diagnosis gradually assumes the character of a post mortem, especially with respect to the desired flight path to Venus. The intended constant operational sequence and stable attitude desired in the cruise will in time lead to an accumulation of acquired data (both science and engineering) with sufficient numbers of samples that deviations from normally expected values in the measured quantities may become easy to distinguish. This can aid in the investigation of failures that occur in the vehicular systems or accidents that may be the fault of the environment.

As the range for communication to the spacecraft increases, it will become impossible to use the alternative low-gain telemetry antenna and any tendency towards marginal operation in the transponder will be increasingly significant. Direct indication of failures by examination of telemetry data will thus be the main technique for assessing system endurance, and the probability of success for this objective will decrease with the increase in flight time.

When the encounter begins, the engineering measurements are deliberately suppressed in favor of the planet science measurements, so that

[1] A committee of experts would debate this decision at some length.

the reception of data directly indicative of failures is no longer possible.[1] Only the inherent characteristics of the received telemetry signal remain as evidence concerning system operation, and confident deductions as to causes or modes of failures become unlikely. In effect, the objective of obtaining failure data during encounter assumes a minor role, and the degree of success to be expected is of low significance to the mission. The availability (if working) of commands to change between cruise and encounter telemetry modes is the sole positive method for inferential failure analysis.

4. Scientific and System Operation Data From Interplanetary Space

With the assumptions used in the considerations of failure diagnosis, it is certain that the vehicle will reach interplanetary space and that initially specific functions will be in correct operation. The probability of achieving the desired engineering measurements as the mission proceeds is in general lower than the probability of failure diagnosis, since there are no alternative or inferential methods for examination of the precise functioning of the on-board systems. Gross functional disorders will of course be readily recognized, but these are viewed as something apart from the deliberate measurements designed into the vehicle. Thus it is possible for the communications capability to be demonstrated even if the subcarrier modulation arrangements fail, since the coherent radio frequency transponder system allows the existence of communications contact to be demonstrated. Response to the "change antenna" commands, which may be recognized on earth by signal power level changes, will show that the communications to the spacecraft are functioning correctly even if the telemetry of data is not correctly in effect. This latter proof can be applied even if the coherent transponder mode is not available, and the exciter is running on its internal crystal oscillator reference.

Whatever the initial probability of success of engineering measurements during the interplanetary flight, it is clear that this probability

[1] Unless the command return to the cruise mode is given.

will decrease as time proceeds, due both to the opportunity for the onset of failures and to the increasing communications range.

It is also notable that the interplanetary aspects of the mission objectives will have a reliability which is substantially lowered by the conduct of the midcourse maneuver, so that there is in a sense a conflict of interests between interplanetary and Venus measurements. With Mariner R, however, Venus is considered to be the prime objective.

A similar observation applies to the success expected for the scientific interplanetary measurements, with the probability about the same as for the engineering. With the present depth of analysis of the Mariner R system designs, it is not possible to state whether the engineering and the science measurements are equally reliable or if there is any significant difference on account of the relative complexities in the data encoding. It might be argued that since there are more measured quantities in the engineering than in the science, the latter has a higher expectation of complete success, but such differences are in all likelihood swamped by the complexities they share in the encoding and telemetry systems. In summary, science and engineering quantities have a comparable probability of being measured as desired, this probability being subject to a steady decline as the mission continues.

5. Science Measurements and Communications from Venus

This is the prime objective of the Mariner R mission. Unhappily, it is the objective which is considered least likely to be achieved. The reasons behind this consideration, restricted to qualitative arguments are as follows:

For the communications, it has been observed previously that the capability falls steadily as the mission progresses, and a point of null effectiveness will be reached intentionally somewhere after the Venus encounter. Here, however, note that not only range is significant, since the proximity of Venus approach depends on success in the maneuver. This is a factor which was not important in any other of the qualitative reliability assessments. Whatever probability is meaningfully considered for Venus range communications, Venus proximity is a requirement which, due to the dependence on a successful maneuver, lowers the expectation of success. Moreover, the contingent effect of any communications degradation is imposed on the probability of achieving the Venus science measurements. All the facts cited in the qualitative assessment to this point indicate that the Venus science measurement has the lowest reliability of any of the topics considered.

This pessimistic conclusion may be further supported by the quasi-quantitative argument presented immediately below.

6. A Numerical Exercise

Since the phases of the mission are serial, the unit[1] strings applicable to successive phases are effectively joined into longer strings as concerns assessments for subsequent and ultimate phases of the mission. In the preliminary quantitative assessment it is reasonable to consider the strings as added in this way. That is, a given unit may appear twice (or more) in a cascaded string of several phases, so that the probability of its successful contribution to the over-all mission will appear more than once in the complete mission assessment. This is a convenient qualitative approximation to the fact that such a unit is called upon more times than one appearance in one phase only.

With this tenet, the units involved in the successive phases of the mission appear as follows.

a. Acquisition

According to a breakdown of the units essential to complete the normal mode for the first phase, the necessary number is 49. Assuming a probability x that each unit performs as specified, this phase has a reliability x^{49}.

b. Maneuver

This involves 50 units, to give a reliability of x^{50}.

[1] A unit is the previously-discussed equipment group, established for the analytical reliability model.

c. Cruise

This involves 49 units to give a reliability of x^{49}.

d. Encounter

This involves 36 units and gives a reliability of x^{36}.

The complete mission uses all these unit contributions to the phases in a serial reliability string effectively 184 units in length, and thus having an over-all probability of success of x^{184}.

If it is assumed for purposes of argument that a mission reliability to Venus is required to be 0.5, then x is caused to satisfy

$$x^{184} = 0.5 \quad \text{or} \quad x = 0.996$$

Using this provisional value for x, it then follows that the individual points of achievement represented by the completion of each phase have reliability estimates of 0.83, 0.69, and 0.60 through acquisition, maneuver, and cruise respectively. This admittedly crude numerical exercise has ignored the time disparities between the various phases, but it does nevertheless suggest that the Venus mission is a challenge to system reliability.

7. Summary of Qualitative Assessment of Mission Objectives

a. Concerning the Objectives

(1) If the transponder and power supply are working, the vehicle may be followed to the limit of communications range. This may show if the maneuver was successful. This can be done with no telemetry (that is, subcarrier modulation--the radio carrier is needed) through cruise or encounter.

(2) To achieve anything more than that in (1) above, more subsystems are required. The resulting reliability configuration is more complex, therefore less likely to function perfectly.

(3) To obtain data on causes and modes of failure, the engineering measurements can be usefully complemented with observations and deductions of diverse quantities as is expedient and practicable. This objective is thus more likely to be attained than merely that of succeeding in the measurements themselves.

(4) Science and engineering measurements are about equal in expectation of success, when made in interplanetary space.

(5) Science measurements of Venus are least likely to be met of all the objectives. They depend on almost complete success in all other functions at some time or other.

b. Concerning Design and Performance

(1) If all 58 units of the reliability model are considered to be equally important, and are all required to survive the entire mission, then, assuming random failure modes and no backup and allowing for repeated processes through the several phases, a mission probability of success of 0.5 needs a unit reliability of x where:

$$x^{184} = 0.5$$

This requires that $x = 0.996$ approximately. This is considered to be a difficult goal to realize with the present complexity of the typical units.

(2) The redundancy in equipment is nil with regard to the complete mission. There is, however, a superfluity of equipment on board for any of the non-Venus objectives.

(3) There is some command redundancy and considerable command backup capability. This can enable certain malfunctions in the CC and S to be overcome and a successful mission thereby obtained. The string of command units around a single CC and S unit or even component, however, is a long one.

(4) Some situations may be met in which it is not possible to know what has happened to the spacecraft, due to internal or external misfortune, or partial failure. In this event the correct application of the command capability is uncertain. This aspect of the operational procedures needs investigation.

(5) In almost all situations, the effective applications of command backup depend on rapid and accurate estimates of the vehicle status. This is hard to secure without the telemetry, and is considerably enhanced by the engineering measurements.

(6) Assessment of the success of the maneuver depends on tracking by doppler data. This implies the use of the coherent transponder mode, and the passage of sufficient time for an accurate new track to be computed from many spaced data samples.

B. Recommendations

1. Outcomes of the Present Studies

The present study is not immediately applicable to the formulation of firm recommendations concerning the Mariner R programs, since it only leads to the establishment of an analytical model but does not exercise it. Quantitative findings will be available as a result of attaching numerical parameters to the symbols contained in the model;

certainly it is almost unnecessary to add that such work should be carried out, with refinement where appropriate. Such refinement is a natural outcome of concentrating the future investigations on areas of the system and its operation which appear to be crucial to the reliability of the complete mission.

The qualitative components of the present investigation lead rather inevitably to the conclusion that the probability of success expected for the complete mission is disappointingly low. It is therefore reasonable to inquire as to what might be done to improve things. Recommendations in this respect may be specifically applicable to the Mariner R system; in addition, it is of interest to consider the basic philosophy behind the design and operation of deep-space probes.

2. Recommendations for the Mariner R System

a. A section of the specification should be devoted to the basics of system redundancy, so that the reasons for not using such in the present design might be appraised.

b. The notion of redundancy by command should be delineated in the specification so that system designers might see where their efforts fitted into the operational concepts.

c. The basics of command backup should be in the specification so that the designers might truly incorporate such backup around as much of the systems as possible without using "serial" equipments and subsystems.

d. Since so much depends on the continuous operation of the power supplies, fault isolation is regarded as mandatory for those systems drawing from the common bus.

e. The possibility of optional (command) adoption of a quiescent mode of operation, especially cruise, should be examined. This would allow a failing power supply to be conserved until the Venus approach, and then used to secure the science measurement objectives.

f. Some effort might be made to provide a minimal analog telemetry scheme of low accuracy to back up the existing complex and accurate arrangements. Such could use an additional subcarrier.

g. The low- and medium-rate data encoding assignments are inherently less reliable than the high-rate ones due to the system arrangements. The quantities coded in each sample rate should be carefully examined with this in mind.

h. The use of highly reliable (admittedly expensive) components has been recommended for OGO in a current PRC quantitative analysis of OGO reliability. The cost of doing this in Mariner should be investigated, especially for crucial systems such as the power supply and communications.

i. The reception of commands at the spacecraft is contingent on the correct functioning of the coherent, phase-locked, receiver section of the transponder. It is thus worth noting that loss of lock could lose the command capability, but that a small modification to the demodulators (in-phase and quadrature) would enable a non-coherent mode to be sustained with a 3 decibel loss in signal strength.

j. The present Mariner R configuration relies on a high-gain antenna to secure communications from interplanetary ranges. The directing of this antenna towards earth is thus essential in the interests of obtaining data from these regions. This directional requirement is currently satisfied as a part of the roll-axis attitude stabilization, and it demands a servo-actuated hinge on the antenna as well as a sensor and reaction-jet assembly to effect the desired control. Things could be much simplified if a fixed antenna were employed, especially if the pattern were such as to exempt the need for roll-axis stabilization. The possibility of doing this is realistic in view of the fact that the gain of the antenna is only needed towards the end of the planetary mission, at which time the orientation of the vehicle with respect to earth is known. Allowing for the various planetary configurations which are likely to apply over the time spread of the launch window, a preset (at launch) antenna direction seems to be worth investigation. The antenna pattern itself would be tapered so as to give gain as required by the range variations over the flight and the relative positions of the vehicle, the earth, and the sun. This scheme would of course utilize yaw- and pitch-axis stabilization, so that fixed solar panels could be optimally illuminated.

Since roll-axis stabilization is needed to perform some of the scientific measurements, control would eventually be necessary. The essential point of importance to the scheme proposed for a fixed antenna is that it removes the dependence of the communications from the attitude control arrangements. This is an improvement towards high functional reliability.

3. Recommendations Concerning the Philosophy of Space Probes

a. It is apparently necessary to define values for the various objectives stated for missions.

b. The influence of national prestige on the possible outcomes should be noted.

c. Since planetary probes involve narrow firing windows, it is not sound logic to load the vehicles with devices which measure space environments to the detriment of a specific planet mission reliability. Planet mission reliability could be enhanced by system redundancy as a payload alternative to devices which measure interplanetary space environments.

d. A general study of space payload optimization, using assessed reliability, values of acquired data, and the total space program outlook would appear to be overdue. That is, there should be something besides the individual view of each project as a single mission with an isolated value.

APPENDIX A

DESCRIPTIONS

A. Mission of Mariner R

The spacecraft is intended to be launched from Cape Canaveral by an Atlas-Agena boost combination. Following separation it will be injected in a Venus-bound trajectory, initially at random attitude and subsequently under controlled attitude with reference to the earth and sun. Sun acquisition will occur about 1 hour after separation, and earth acquisition about 167 hours after launch. The delay between these events is to avoid the possibility of aborted acquisitions.

After about 180 hours, a midcourse flight path correction will be made according to computations of the actual path observed[1] up to this time. The impulse is initiated by command and is implemented by controlled orientation of the spacecraft so as to provide the required vectoring. During this maneuver, the earth-sun references will be deactivated. They will be re-acquired once the boost correction has terminated, in a manner similar to the original acquisitions at the start of the flight.

A cruise period of some months now follows, the exact time depending on the planetary positions at the launch date. About 10 hours before the Venus fly-by, which is to be about 20,000 miles distant at the closest point, special scientific observations are automatically begun. Subsequently, the same observations are commanded from the earth as a backup against automatic sequencing failure. Some time following this event the mission is deemed to be complete, and transmission is terminated and the antenna is oriented to the sun.

During all phases of the flight, including injection, real-time telemetry is sent to the deep space instrumentation facility (DSIF). Phase-locked f-m transmission in L band is employed, with a radio transponder which also receives commands from the DSIF to supplement the

[1]Doppler measurements are used for this.

automatic sequence capability of the onboard vehicle-control system. The acquired data is of two origins. Some applies to the internal monitoring of the spacecraft mechanical and electrical quantities, while the other (which is not measured in all phases) is scientific and pertains to the space environment, both in interplanetary space and in proximity to Venus. Thus, during the entire mission, information of scientific value concerning the physical quantities in space, and information of engineering interest concerning the performance of the onboard equipment will be provided.

B. The Mariner R Spacecraft

The vehicle Mariner R (R denoting the inclusion of some Ranger components) weighs 446 pounds at launch. Once in free flight, its shrouds are discarded and antennas and probes are erected, so that it becomes an assembly measuring several feet over-all, excluding the solar power cells. These cells occupy two panels totaling 27.4 square feet in area. The basic airframe is a hexagonal cylinder and the various payload assemblies are fixed to the faces of the cylinder. A rocket motor is mounted with its thrust along the roll axis, or center line of the basic cylindrical structure. A parabolic antenna is hinged for a single degree of freedom, allowing inclination to the roll axis. The solar cell panels are erected rigid in the plane defined by the yaw and pitch axes, and are, except during maneuvers, aimed at the sun by pitch and yaw attitude control. Control of roll and antenna hinging enables the antenna to be directed to the earth.[1]

The frame is open and the various subassemblies are exposed to the environment. Their surfaces are finished individually, and differ according to the desired thermal radiation emissivities. There is apparently ample space for the disposition of the assemblies, especially the electronics. Magnesium is the normal supporting material for the frames and cases.

[1] Provided the planetary configuration is within certain limits.

Electrical power at a nominal 80 watts comes from the solar cells and intermediate storage batteries. This is continuously available.

Propulsion power comes from a hydrazine propellant, which is catalytically decomposed. This is a one-shot impulse, controlled by duration increments in the burning time.

Telemetry with the DSIF is maintained continuously at 960 mc using subcarriers with phase modulation. It is a transponded signal, and is normally phase coherent (at radio carrier frequencies) with the command input carrier received from DSIF at 890 mc. Telemetry data and word/frame synchronization use separate subcarriers. The telemetered data itself is time multiplexed among the various data sources. The data is digitally encoded, and the pulse word, frame rates, and function sequencing are controlled internally by the data encoder and the central computer and sequencer in the vehicle. Basic data pulse rates are initially 33.3 per second, and then, following earth acquisition, 8.3 per second for a long range capability. Either an omni (low gain) or a parabolic (high gain) antenna can be employed.

Attitude control during normal flight is about yaw and pitch axes using optical sun sensors and torques from cold-gas jets, so that the roll axis points to the sun, as then do the solar panels. Roll control is also effected by gas jets; and error sensing is inherent in the parabolic antenna aiming, which is by optical earth-light alignment.

During the midcourse flight correction maneuver, special commanded orientation of the vehicle is effected by an autopilot system, using the same gyro references as also serve the attitude-control system. These gyros are necessary during the controlled-attitude search excursions required for initial acquisition by the sun and earth sensors. While under flight correction, attitude-control torques come from the rocket motor, using jet vanes, according to the dictates of the autopilot.

Except during maneuvers, scientific instruments will be in use to make measurements of: radiant energy (13.5 and 19 mm) at Venus, infrared radiations (8-9 and 10-10.5 microns) at Venus, and, in interplanetary regions, charged particles, plasma, and micrometeorites.

The data is encoded and transmitted in real time to the DSIF. In total, 21 separate scientific quantities are telemetered in time multiplex.

Internally the vehicle makes measurements of its own systems and functions at all times after injection (except at Venus) as follows: there are measurements which pertain to the signals, discrete events, and functions of the various subsystems such as AGC voltages, reception of commands, antenna hinge angle, servo error, etc., of which a knowledge is essential to the control of the flight; there are measurements of quantities in the electrical power supply, compressed gas supply, and similar vehicle utilities; there are measurements of environmental quantities which may vary without having any further significance for the system functions, such as temperatures at various points on the airframe and component boxes. These latter measurements are intended to aid in assessing faults, failures, and accidents. The total of all the engineering quantities that are telemetered is 48. There are five supplementary spare channels[1] in the engineering telemetry assignments, giving a grand total of 53 channels. These are time multiplexed at various sampling rates among one another and commutated with the science data in a sequence of sample-time allocations that depends on the on-going phase of the mission: launch and earth acquisition, midcourse maneuver, cruise, and encounter. Some of the instruments are periodically calibrated at intervals throughout the mission. The ultimate measure of the success of the mission is in terms of the performance of the science experiments and engineering measurements. Mission reliability, therefore, must take account of tolerance, recovery, readjustment, redundancy, and so on, appropriate to the specified experimental environment.

[1] Three at one sample per 370 secs and two at one sample per 3,700 secs.

APPENDIX B

APPROACHES TO RELIABILITY ASSESSMENT

For quite some time it has been recognized that the classical reliability measure is unsuitable when applied to systems in which some internal failures do not cause catastrophic system failure but, rather, result in degraded but acceptable system performance. A number of reliability measures have been suggested to overcome the classical measure's inadequacies. However, partly because of their relative newness and partly because each, in general, must be tailored to the particular system under study, they (or at least the common basic concept underlying them) have not had widespread understanding and application. PRC has recognized that evaluation of spacecraft reliability must most realistically employ a nonclassical measure and, in fact, has utilized such a measure in developing a number of reliability models.

The primary purpose of this discussion, then, is to present a heuristic description of the measure used in model formulation, avoiding as much as possible the mathematical details and symbology. Another purpose is to explore the subject of the preceding paragraph in more detail. Specifically, the classical measure and PRC's version of a nonclassical measure are discussed and compared, first relative to a simple device (a two-way radio) and then more generally. Among the consequences it is established that the classical approach is essentially a special case of the nonclassical one.

The reliability of a device meant to perform a single function (e.g., a radio receiver) is normally expressed by the probability that all elements of the device required for minimally satisfactory performance will operate at any given time. This is the basis of what may be called the classical approach to reliability formulation. But even for the simple, single-function device it can be noted that a disquieting ambiguity appears in the statement of what reliability means. What is "minimally satisfactory performance"? Why use it in a definition of reliability anyway? How about "best performance," or "average performance"? What about exterior circumstances (the radio, through no fault of its own, will not deliver the same performance in an electrical storm as on a clear summer night); and so on.

As such considerations have penetrated, and equipments to which reliability analysis must be applied have become more complex--multi-functional, with many possible states of operational effectiveness--it has become increasingly clear that a more flexible and directly meaningful measure of operational reliability is necessary. At PRC and elsewhere a "figure-of-merit" approach has as a consequence evolved.

In full generality, this approach considers, from the beginning, the use to which an equipment or system is to be put, expressed by its actual use profile; the environment it will have to deal with; the possible levels of degradation that can occur in the performance of each of its functions; and the value to over-all mission success of every such possible degraded function, generally with dependence on time during the mission. Of course, reality, in terms of lack of information, often imposes limitations on one's ability to detail system operation so fully, but these limitations are now at least <u>clearly recognized sources of approximation</u>, not ambiguities in definition.

Before analytically comparing the classical approach with PRC's concept of the figure-of-merit approach, let us better set the scene by emphasizing the foregoing remarks with an illustrative example of a reliability analysis for a two-function device. The ideas of the new approach should then arise naturally as alternatives to the contortions necessary to fit the classical approach to the device.

Consider a device, e.g., a two-way radio, that is meant to perform one or both of two functions (reception and transmission) at various times during its employment. Its equipment elements can be considered as falling into three classes: those required only for the first function (e.g., the receiver), only for the second (e.g., the transmitter), and for both (e.g., the power supply). Suppose the mission requires communication with only two other stations, one near and one far away. Assume for simplicity that all external factors are such as to permit satisfactory communication (in terms, say, of a signal/noise ratio of 20 db or better) essentially 100 percent of the time when all equipment elements are in perfect order.

What is the classical reliability of this device for a one-week period? It is the probability that all equipment elements will work perfectly for one week. But suppose that 80 percent of the time only reception is necessary. Why should the failure of a transmitter element then be considered as causing system failure to the same degree as the failure of a receiver element? Again, what if the far-away station is only communicated with to get an advanced weather report, while the near station provides hour-by-hour command data? Should the failure of one power amplification stage, resulting in loss of transmission capability to the far station, be considered a cause of system failure equal to the failure of the local oscillator providing tuning to the near station?

It may be replied that the preceding argument is valid enough, but if the device's mission is appropriately defined as a minimal one--e.g., satisfactory reception only of the near station's commands--then the difficulties are obviated, and reliability is once more merely the probability that all equipments of a certain class will operate, in this case the class of receiver and power supply elements needed for reception of the near station's signals. Unfortunately, it is a rare radio purchaser who would be satisfied with such "reliability." Thus, the classical approach is seen to be too restrictive to permit truly meaningful and/or acceptable definitions of complex equipment reliability.

Let us now consider the figure-of-merit approach applied to our radio. There are four functions to be performed, reception and transmission for the near station and reception and transmission for the far station. From an analysis of the frequency and context of the messages involved, let us agree that these functions have the following relative values, normalized to give a total value of one (it is usually a significant exercise in itself to establish these values meaningfully): reception of near station messages, .60; reception of far station messages, .10; transmission to near station, .25; transmission to far station, .05.

Now, consider all possible operability states of the radio equipments, that is, all possible mutually exclusive configurations of elements when some are operable and some have failed. The configuration existing when all equipment elements are operable is, for example, a state--the "perfect" state. Another state, for example, is the configuration wherein all elements required for reception (alone) are inoperable and all elements required for transmission are operable. Clearly, the set of all possible states ranges from the "perfect" state through all states defined by configurations containing varying combinations of operable and inoperable elements to the "imperfect" state in which every element is inoperable. To each possible configuration can be associated a probability of its occurrence, calculated by standard combinatorial methods applied to a reliability block-diagram and from failure rate data for each element. Let S_i be the set of all possible states, and $P(S_i, t)$ the probability of occurrence of state S_i at time t.

When the radio is in any given state S_i, it will be able to perform some subset (from all to none) of its four possible functions (at a stated performance level, under stated conditions, for each). According to the totality of such functions it can perform, a value, V_i, can be assigned to the state S_i. Alternatively, as a refinement when complete mission profiles (i.e., statements of functions desired to be performed in each time interval) are available, the value can be determined from those functions it is desired to perform and which can be performed. For simplicity here, consider only the former definition of state value.

For the radio, since a value was assigned to each function individually, V_i is then calculated as the sum of the values of all functions permitted by state S_i. Thus, states for which all functions are possible have a value of 1.0; those for which all but transmission to the far station are possible, .95; those for which only reception of the near station is possible, .60; etc.

Now $P(S_i, t)V_i$ is the component of the expected value[1] of the radio's performance arising from possible state S_i, at time t, and

[1]That is, the mathematical expectation of the radio's performance value, V.

$$V(t) = \sum_i P(S_i, t) V_i$$

is the expected value of the radio's performance at time t, calculated as the weighted average over all possible states of the values of these states. Finally,

$$\overline{V} = \frac{1}{T} \int_0^T \sum_i P(S_i, t) V_i \, dt$$

is the average value over the mission period (one week) of T units of time. $\overline{V}$ is the suggested reliability figure-of-merit for the radio. With the normalizations indicated, $\overline{V}$ lies between zero and one, and is larger the greater the expected performance value, operational reliability, or operability of the system. It is therefore valid and meaningful for the comparison of alternative radio designs when it is desired to select the better in terms of the more reliable average performance. In addition, to the degree that the basic data is truly realistic it provides a meaningful absolute measure of the radio's expected performance.

We note two relationships between the figure-of-merit and classical assessment formulations. First, when a definition of "satisfactory performance" for the classical approach has been made, the list of equipments that must be operating to provide this performance must be given in order to calculate the probability that they will in fact be doing so. This list can be translated into a list of "good" states--those in which at least this set of equipments is operating. The sum of the probabilities of the occurrence of these good states, each of which is evaluated in the figure-of-merit approach, is then equal to the classical reliability. It is thus seen that classical reliability is the figure-of-merit approach's expected value of the states when the value of each such good state is taken to be one and the value of each bad (unsatisfactory performance) state is zero.

From this point of view, then, the figure-of-merit approach generalizes the classical approach to take into account partial performance degradations in a continuous, rather than in a more or less arbitrary, black-or-white, manner.

Secondly, whereas classical system reliability statements require completely "satisfactory" system performance throughout the stated mission time period, with zero value arising otherwise, the figure-of-merit approach takes into account the gradual accumulation of value actually provided by most systems (other than one-shot devices). It does this through the time integration of expected value as exhibited in the second equation above.

APPENDIX C

AN EXAMPLE OF PROCEDURE

While it is meaningless to estimate failure rates for the several units at this level of investigation, some of the techniques that would be used in applying the model can be brought out by an example based on artificial estimates. The example will be restricted to a single element of expected value for one phase. The integration of such elements into a figure-of-merit is straightforward and is well exemplified in Appendix B.

Before considering a particular path, the normal mission will be examined. Among the functions required for a normal mission is the science measurement function. Study of the system diagrams and of the flight sequence prompts the following statements regarding science measurements:

1. The function is not turned on (except possibly for testing) during the 185[1] hours of phases I and II.

2. The function operates in the cruise mode during phase III for 2,628 hours (of a four-month mission) and in the encounter mode for 67 hours in phase IV.

3. Units 101, 102, 103, and 211 must all be up to provide the function.

For a normal mission the reliability of the science function is the product of the reliabilities of these four units over all four phases. Let us assume the following failure rates apply for each unit.

Standby - λ_s = 6×10^{-6} failures per hour
Cruise - λ_c = 15×10^{-6} failures per hour
Encounter - λ_a = 30×10^{-6} failures per hour

[1] All times cited in this example are approximate.

The higher failure rate for the encounter mode is predicated on the added loading for planet experiments and the more rapid telemetry rate. The reliability of each of the units during phases I and II is

$$P(X_u, \text{I-II})e^{-185\lambda_s} = .9989 \tag{C-1}$$

For the entire function the reliability through phase II is

$$[P(X_u \text{I-II})]^4 = (.9989)^4 = .9956 \tag{C-2}$$

Similarly, the unit reliability during cruise is

$$P(X_u, \text{III}) = e^{-2628\lambda_c} = .9613 \tag{C-3}$$

And the functional reliability during this phase is

$$[P(X_u, \text{III})]^4 = (.9613)^4 = .8540 \tag{C-4}$$

In phase IV, the unit reliability is

$$P(X_u, IV) = e^{-67\lambda_a} = .9980 \tag{C-5}$$

and the phase IV functional reliability is

$$[P(X_u, IV)]^4 = (.9980)^4 = .9920 \tag{C-6}$$

If the science function reliability is denoted as P(100), then

$$P\left[(100)\ I,\ II,\ III,\ IV\right] = (.9956)\ (.8540)\ (.9920) = .8434 \tag{C-7}$$

The reliability of the other major functions over a normal mission can be derived in a similar manner with appropriate failure rates applied throughout the mission. Let us assume in this drastically simplified case that each of the remaining functions is characterized by a reliability of .8 over the mission. Since there are seven such functions, the reliability of the normal mission would be

$$P(\text{normal}) = (.8434)\ (.8)^7 = .1769 \tag{C-8}$$

Now, the path to be investigated is specified briefly as one which traverses phase IV without measuring science but with all other required functions available and with the space probe in the correct trajectory and attitude. It is not necessary under this specification to exclude the possibility that the science function might have failed in a prior phase. Accordingly, the probability that the science function would be lacking in phase IV is the same as the probability that it failed to survive the entire mission. This is given by

$$1 - P\left[(100)\ \text{I, II, III, IV}\right] = 1 - .8434 = .1566 \qquad \text{(C-9)}$$

Some reflection on this expression is in order because it sums up all of the probability contributions of a large number of routes. One typical route involves the failure of unit 101 in phase 1, and no other failures throughout the mission. Other routes would result from single unit failures in later phases, and still others from various combinations of other failures. In fact, because of the path specification, all possible failure combinations (which includes the case of no failures anywhere) over the four phases constitute the route possibilities. For this single path, demanding a failure of at least one of four units in any of four phases gives rise to $(J + 1)^N$ routes [1] where

$$N = \text{Number of units} = 4$$
$$J = \text{Number of phases} = 4$$

so that the total number of routes is 625. One of these routes consists of the connection of normal paths with all required units up, but any of the remaining 624 routes will lead through the specified path.

[1] Since a given unit can fail in no phase, phase IV, phase III, phase II, or phase I--a total of 5 cases.

The probability of traversing phase IV with the science function down was computed as .1566 in expression (C-9). The probability of having all other required units up during this phase is derived from the probability of a normal mission, but with the uncertainty of the science function removed. The normal mission probability was calculated as .1769 in (C-8) and the science function was included through the factor .8434. If this factor is divided out, the probability of achieving a normal mission except for science measurements is .2097. This factor together with the probability of a failure in the science measurements gives the path reliability:

$$(.2097)\,(.1566) = .0328 \tag{C-10}$$

This gives the probability of following the specified path along any of the 624 allowable routes.

At this point the path value should be introduced; however, the example does not include a value assignment since the method of doing this has not been formalized. When a value assignment has been made, it is multiplied with the path reliability from (C-10) and the product is listed as an element of expected value for phase IV. The summation of all such elements will be the expected value for phase IV, and the overall figure-of-merit can be derived by the averaging technique discussed in Appendix B.